TEXT FLY WITHIN
THE BOOK ONLY

COMETS

BY

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TO MY WIFE

MARY FRANCES PENDER OLIVIER

THIS BOOK IS AFFECTIONATELY
DEDICATED

PREFACE

The study of meteoric astronomy, especially in its theoretical aspects, gradually drew the author's attention to the need of a closer study of comets. This in turn led back to the origins of all the minor bodies of the Solar System and to similarities that exist between them. The appearance of the important book by T. C. Chamberlin, *The Two Solar Families*, also stimulated this interest. Further no recent book on comets, which covers the theoretical side, is available in the English language. Consequently it seemed that a book of moderate size, which would cover briefly the history of the subject and the present theories of origin, constitution, changes, and dissolution of comets, would be useful to the astronomer who does not specialize in the subject, as well as to the average intelligent reader. It is the author's aim to fill these requirements, leaving out entirely any mathematical discussions.

This book does not claim to cover the whole field; only selected comets are described. Also important work by some investigators is

perforce omitted. The book is intended as a sequel to older books on the same subject, such as for instance Chambers' *The Story of the Comets*, rather than to replace them. It is further intended as a direct sequel to the author's book *Meteors*, as new information and discoveries have permitted a considerable extension of certain theories tentatively advanced in its closing chapters. Also the ties between comets and meteors are so numerous that some knowledge of the one is necessary to understand the phenomena connected with the other.

The author desires to express his sincere appreciation to his colleague, Dr. S. G. Barton, for kindly reading and correcting the manuscript, and for helpful criticism in its preparation.

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CHAPTER I

Historical Review

"When beggars die, there are no comets seen,
The Heavens themselves blaze forth the death of Princes."

—Shakespeare, *Julius Cæsar.*

Records of comets have come down to us from remote antiquity. It is evident that the appearance of a brilliant and unexpected comet in the sky must have caught the attention of men long before any permanent record of it could have been left for posterity. But from the centuries preceding the Christian era on, numerous accounts of comets have survived, as well as some theories advanced by Greek and Roman writers.

The very word comet is derived directly from the Greek word Κομήτης, the long-haired one. Many books give the Latin word *coma*, hair, as being the ancestor. Hence the comet was "a hairy one." This name came quite naturally from the long tails so often accompanying the larger comets, and which attracted attention as being unique in form among other heavenly bodies, all of which were considered spherical.

For most older comets the Chinese left more complete records than European nations, and it is due largely to their observations that approximate orbits can be computed for some comets which appeared over two thousand years ago. The Japanese also left fewer similar accounts. Comets are mentioned in the extensive literature from the Euphrates Valley which has been slowly unearthed and translated. As a specimen we quote that referring to the comet of 1140 B.C. The tablet gives an account of a campaign in Elam and states "a comet arose whose body was bright like the day, while from its luminous body a tail extended, like the sting of a scorpion."[1]

In 344 B.C. a comet is mentioned by Diodorus Siculus as follows: "On the departure of the expedition of Timoleon from Corinth for Sicily the gods announced his success and future greatness by an extraordinary prodigy. A burning torch appeared in the heavens for an entire night, and went before the fleet to Sicily."[2]

[1] A. H. Sayce, *Babylonian Inscriptions*.
[2] *Bibliotheca Historica*, XVI, 11; also Plutarch, *Timoleon*.

In 146 B.C. a comet appeared that is described thus by Seneca: "After the death of Demetrius king of Syria, ... there appeared a comet as large as the Sun. Its disc was at first red, and like fire, spreading sufficient light to dissipate the darkness of night; after a little while its size diminished, its brilliancy became weakened, and at last it entirely disappeared."[3]

In 43 B.C., just after the assassination of Julius Cæsar, Suetonius thus describes the comet then visible: "A hairy star was then seen for seven days under the Great Bear. . . . . It rose at about five in the evening, and was very brilliant, and was seen in all parts of the Earth. The common people supposed that the star indicated the admission of the soul of Julius Cæsar into the ranks of the immortal gods."

These quotations will give a general idea of the effects produced upon the minds of classical writers by the appearances of bright comets. Humboldt states that:[4] "While these bodies were considered by the 'Chaldeans of Babylon,' by the greater part of the Pythag-

[3] *Quaest. Nat.*, VII, 15.

[4] *Cosmos*, 4, 558–60.

orean school, and by Apollorinus Myndius, as cosmical bodies reappearing at definite periods in long planetary orbits, the powerful anti-Pythagorean school of Aristotle and that of Epigenes, controverted by Seneca, declared comets to be productions of meteorological processes in our atmosphere." Seneca stated: "For I do not think comets are a casual outburst of fire, but belong to the eternal works of nature. For why should it surprise us that comets, so rare a phenomenon, should not yet be subject to the regulation of any known laws and that their origins and ends should be hid from us, who see them only at immense intervals?"

The authority of Aristotle, which grew to such tremendous proportions in the Middle Ages, in this case played into the hands of the popular beliefs, and the more ancient Chaldean theory, brought into Europe doubtless by Pythagoras, was set aside. It is only just to add that Aristotle gave reasons and arguments, even if erroneous, for his conclusions that comets were mere meteorological phenomena.

It is quite evident that most persons, high and low, considered comets as portents and

prodigies, and their coming doubtless caused universal fear. This has not entirely ceased even in our own day, when their nature is better understood, and their orbits can be calculated. Literature is rich in allusions to the awe inspired by comets. Shakespeare has among other:

> "Comets importing change of times and states,
> Brandish your crystal tresses in the sky, ..."
>
> —*Henry VI.*
>
> "As stars with trains of fire and dews of blood,
> Disasters in the Sun."
>
> —*Hamlet.*

And then the famous quotation from Milton:

> "Satan stood
> Unterrified, and like a comet burn'd
> That fires the length of Ophiuchus huge
> In th' Artick sky, and from its horrid hair
> Shakes pestilence and war."

In Homer's *Iliad*, the helmet of Achilles is described as being

> "Like the red star, that from his flaming hair
> Shakes down diseases, pestilence, and war."

In Thomson's *Seasons* we find the following verses, which could have been written only

after the fact was known that many comets returned at regular intervals:

> "Lo! from the dread immensity of space
> Returning, with accelerated course,
> The rushing comet to the sun descends:
> And as he sinks below the shading earth,
> With awful train projected o'er the heavens,
> The guilty nations tremble."

All through history we find that the appearances of comets were considered as prophecies of deaths of kings, famines, wars, pestilences, and other ills to mankind. Halley's Comet, to which a separate chapter will be devoted, happened to come nearly at the times of many important events in human history. It is not too much to say that some of its appearances actually had an influence upon contemporary events, due to the mental reactions of those who saw it. It should be needless to add that its physical effects upon the Earth were in all cases quite negligible.

It is strange that Ptolemy, the author of the *Almagest*, the earliest great textbook on astronomy which has come down to us, entirely ignored the subject of comets. This is a great pity, as we should like to know what his and contemporary scientific opinions were. We may safely conclude that in the Middle Ages,

with those who studied and thought of such matters at all, the conclusions of Aristotle were generally accepted in this as in most other scientific matters.

As late as the sixteenth century, the father of French surgery, the eminent Ambroise Paré, described the comet of 1528 as follows: "This comet was so horrible, so frightful, and it produced such great terror in the vulgar, that some died of fear and others fell sick. It appeared to be of excessive length, and was of the color of blood. At the summit of it was seen the figure of a bent arm, holding in its hand a great sword, as if about to strike. At the end of the point there were three stars. On both sides of the rays of this comet were seen a great number of axes, knives, blood-colored swords, among which were a great number of hideous human faces, with beards and bristling hair." It is only just to the memory of this great man to say that he was but eleven years old in 1528, so his recollections of its appearance were doubtless affected by the wild stories he had been told by others.

However, fifty-six years before, Johann Müller of Königsberg, known as Regiomon-

tanus, had made real observations of the positions of the comet of 1472 on different nights, showing that he at least considered it a heavenly body, worthy of study. This comet was visible three months, and its approximate orbit has been computed on the basis of his observations. Similar rough orbits, based mostly on Chinese observations have been computed for over forty comets which were seen previous to 1472 A.D.

When the bright comet of 1577 appeared there was at last a man who took up the problem in a scientific way. This was the famous Tycho Brahe. He made an elaborate series of observations at his own observatory, and was able to compare them with others made at Prague. The lack of parallax indicated by the two series at once showed that the comet was certainly more distant than the Moon. He endeavored to represent its path by a circular orbit external to that of Venus. At any rate this work fully disproved the hypothesis that comets were ordinary "meteors," as the word was then used. His more famous pupil, Kepler, worked on the comets of 1607 and 1618. He concluded that comets traversed our system in rectilinear

orbits. He considered them as numerous as fishes in the sea. His further conclusions as to their nature are so curious, coming from a man who made such eminent discoveries as to orbits, that they are worth quoting in part. It shows how even such a man is influenced by the beliefs and superstitions of those about him. He says: "They are not eternal, as Seneca imagined; they are formed of celestial matter. This matter is not always equally pure; it often collects as a kind of filth, tarnishing the brightness of the Sun and stars. It is necessary that the air should be purified and discharge itself of this species of filth, and this is effected by means of an animal or vital faculty inherent in the substance of the ether itself. This gross matter collects under a spherical form: it receives and reflects the light of the Sun, and is set in motion like a star. The direct rays of the Sun strike upon it, penetrate its substance, draw away with them a portion of this matter, and issue thence to form the track of light we call the tail of the comet. This action of the solar rays attenuates the particles which compose the body of the comet. It drives them away; it dissipates them. In this manner the comet

is consumed by breathing out, so to speak, its own tail."

We may remark that in all this mass of conjecture and foolishness there are certain germs of truth, as we shall see later. Also, before Kepler's time, at least two observers, Jerome Fracastor (1483–1543) and Peter Apian (1495–1552) had observed that comets' tails always point away from the Sun.

That the orbits of comets are either much elongated curves or parabolas was proved by Dörffel of Saxony from his work on the comet of 1680. This comet was visible eighteen weeks. Borelli had, however, in 1665 already expressed the idea that the orbit of the comet appearing at the end of 1664 was parabolic.

Newton, however, proved that according to the law of gravitation a body could move around the Sun, situated at the curve's focus, not only in an ellipse but also in a parabola or hyperbola. Halley, the friend and contemporary of Newton, undertook the calculation of the orbits of twenty-four comets for which there were, in his opinion, enough observations. He was struck with the great similarity of the elements of three of the comets, and on the basis of this and the

approximately equal intervals between their appearances, he predicted the return of the comet, now known by his name. The triumphant vindication of his prediction finally put cometary astronomy on a firm, scientific basis. A full account of this will be given later in the chapter on Halley's Comet.

Before leaving the historical side, a few more interesting examples will be quoted.

The most striking example from the Old Testament is found in the verse: "And David lifted up his eyes, and saw the angel of the Lord stand between the earth and the heaven, having a drawn sword in his hand stretched out over Jerusalem."[5] That a comet is here meant is made the more certain by a later statement by the great Jewish historian Josephus, who in his accounts of the prodigies which foretold the destruction of Jerusalem by Titus says: "Thus there was a star resembling a sword which stood over the city, and a comet that continued a whole year."[6]

Apropos of comets Bayle quotes a remark said to have been made by Henry IV about the astrologers who had been forewarning

[5] I CHRON., xxi, 16.

[6] Josephus, *Jewish War*, 6, 5.

him about his death, "They will be right some day, and the public will remember the one prediction that has come true, better than all the rest that have proved false."

The same writer speaking of the pride of men who thought their deaths so important that God must send a comet to announce it, "If we had a just idea of the universe we should soon comprehend that the death or birth of a prince is so insignificant a matter, compared to the whole of nature, that it is not an event to stir the heavens."

The comet of 1680 inspired the famous Madame de Sevigné to write as follows, on January 2, 1681, to the Comte de Bussy.[7] "We have here a comet—it has the most beautiful tail that could possibly be seen. All the great personages are alarmed, and firmly believe that heaven, occupied with their loss, is giving intelligence of it by this comet. It is said that Cardinal Mazarin being despaired of by his physicians, his courtiers considered it necessary to honor his last hours by a prodigy and to tell him that a great comet had appeared which filled them with

[7] Guillemin, *World of Comets*, 30, 1877.

alarm for him. He had strength enough to laugh at them, and jestingly replied that the comet did him too much honor. In truth everyone should say the same, and human pride does itself too much honor in believing that when perforce we die it is a great event among the stars."

An amusing proclamation was issued by the Town Council of Baden,[8] Switzerland, in honor of the comet visible in January, 1681, whose "frightful long tail" extended over 80°. Among other instructions "all were to attend Mass and Sermon every Sunday and Feast Day, and none was to leave church before the sermon or remain away without good reason: to abstain from excessive Carnival festivities and playing and dancing, whether at weddings or other occasions. Evening drinks were to be on a modest scale and to finish at nine, after which all were to go home quietly, without shouting in the streets. . . . ."

These quotations show that, even at the end of the seventeenth century, it was exceptional when a person was found who did not still believe in comets as portents of evil.

[8] *Jr. B. A. A.*, 37, 241, 1927.

One of the most curious opinions is that attributed to Bodin[9] by Bayle who says the former believed "that comets are spirits, who having lived innumerable ages on earth, and being at last near death, celebrate their last triumph or are brought again to the firmament as shining stars."

The writer was told personally by a man, who in 1910 was a small boy living in a town in the interior of Asia Minor, that the report of the coming passage of the Earth through the tail of Halley's Comet created much consternation in his neighborhood. Many understood that their safety depended upon getting into water up to their necks, to avoid the harmful effects, hence as the day approached water barrels were filled everywhere in anticipation. Apparently, however, they were not used.

The belief in the baleful influences of comets had not entirely died out up to very recent years, even with persons of some intelligence. Among many examples that could be quoted is that of the comet of 1861 which was supposed to announce the beginning of the

[9] Bayle's *Dictionary*.

Civil War in America. For the benefit of astrologers and similar charlatans, who work on the superstitions of the ignorant, it is too bad that a great comet did not appear in the summer of 1914, just as the World War began! But no bright comet was sufficiently obliging.

CHAPTER II

General Statements

> "And there appeared another wonder in heaven; and behold a great red dragon, having seven heads and ten horns, and seven crowns upon his head. And his tail drew the third part of the stars of heaven, and did cast them to the earth."

Comets are of all bodies in the Universe, or certainly in the Solar System, the most difficult to explain both as to their origins and behavior. Even the same comet at different returns does not necessarily look like itself, and very likely some surprising and unexpected changes may take place within a period of a few days or sometimes in a few hours.

The typical comet, however, has three distinct parts: the nucleus, the coma, and the tail. In many cases, particularly with faint comets, the nucleus and tail seem to be missing. Hence, not unnaturally, the statement is often made in textbooks and elsewhere that the coma is the one part that must be present, if the body is still to be classed as a comet. The writer desires to take strong exception to the implication of this definition,

if not to the statement itself. It seems to him certain that the coma could not exist without a nucleus, which would serve to give enough mass to hold the body together, at least to whatever extent it is so held. That is, of course, unless there are forces in action within the coma of which we know nothing, or the coma material is in an unknown physical condition. While improbable, neither of these possibilities can be ignored, and accepting them explains many things now far from clear. Assuming, however, that the coma obeys laws with which we are familiar, then it would appear that the attraction within such a mass of gas and small particles would not be enough to hold it together, without a nucleus, exposed as it is to tidal actions on each visit to perihelion.

It seems necessary, therefore, to admit that all comets must have nuclei, whether we see them or not. This last is not a great difficulty, because we have every reason to believe that a comet's nucleus is not one solid body, but a group of meteorites of assorted sizes. When this group is large and condensed enough, it will appear as one or more almost star-like points. When it is too small to be visible,

though still compact, or when its individual members have scattered out somewhat, no nucleus can be seen. In such a case we would find a coma apparently lacking a nucleus.

Sometimes, probably the contrary takes place, and the coma is lost, while the nucleus remains. This is, we infer, the explanation of such a body as asteriod No. 944. In this case, the nucleus evidently was not scattered. It may be explained on several hypotheses, some much more probable than others: (i) the nucleus is one solid mass, (ii) it consists of several large masses so near together that perturbations have no appreciable effect. These are merely suggestions, there is no proof that either of them is correct.

In the long run it seems that no comet can permanently retain all the characteristics of a typical comet. We may go further and say that most comets will be wholly dissipated. The order of loss is: first the material that forms the tail, second the coma material (after which the comet will usually be invisible), lastly the nuclear material. This last when well distributed along the orbit probably forms the usual type of annually recurring meteor stream.

So far only one comet has been spoken of as though it always lived its life alone. But we have comet groups, which consist of several moving in almost the same orbit, but spaced at irregular intervals along it. Did not all these once form parts of a supercomet which broke up into a number of smaller ones? Then we see examples like Biela's Comet, where a small comet divides into two before our very eyes. Then we have complex examples like Tempel's Comet, the Leonid group which furnishes the great showers at thirty-three-year intervals, and scattered meteors all around the huge elliptical orbit. This last fact is proved by at least a few Leonids being met every November (see p. 186). But comet, and the dense group, and scattered Leonids all move in the same orbit.

Without going further into the matter here, it seems that comets are aggregations which in time lose their typical cometary character, and whose units are scattered. As there seems no way of explaining how a comet can be rebuilt, this fact makes any theory of their origin difficult, for it seems hard to admit that, if of planetary age, they could have survived so long. These questions will be dealt with more fully in a later chapter.

Comets move around the Sun in orbits which are conic sections, the Sun being at one focus. Three types of orbits occur, elliptical, parabolic, and hyperbolic. A superficial division of published orbits would show about one-quarter in the first division (100 ±), three-quarters in the second (300 ±), and about a score in the third. A smaller list[1] of 347 more accurate orbits gives in each division mentioned the following numbers: 60, 275, and 12 respectively. The ellipse is the only closed orbit of the three types, therefore any body moving in either a true parabola or a hyperbola would simply revolve once about the Sun and then go off into the depths of space. Nor would it ever return, as it would be moving in an open curve. On the contrary, a body in an elliptical orbit will move around the Sun in a definite period, returning at regular intervals.[2]

Are then the vast majority of comet orbits, classed as parabolic, really parabolas? And if

[1] W. W. Campbell, *Adolph Stahl Lectures on Astronomy*, 33, 1919.

[2] Strömgren, *Vierteljahrsschrift d. Astr. Gesellschaft*, IV, 1910. Also, Fayet, *Recherches Concernant les Eccentricités des Comètes*, 1906.

not, why are they so called? There is every reason to believe they are not—indeed, due to planetary perturbations, a comet *cannot* move in a true parabola. For if the comet started toward the Sun in such a curve, the least increase of its motion due to any planet would make the orbit hyperbolic, the least decrease would make it elliptical. One of these contingencies must always occur.

But we only see a small part of the total orbit, that which lies near perihelion. So when the period is very long, that portion of the orbit, though the latter is a true ellipse, cannot be distinguished from a parabola. This is due to the inherent imperfection of any observations made by human beings, and besides a comet is a more difficult object to observe accurately than a star. Therefore, a parabola fits the observations as well as any other curve, and is far easier to compute than an ellipse. So we say that they move in parabolas though it is understood they actually do not, only our observations are not accurate enough in such cases to give the elements of the very elongated ellipse in which the comet really moves.

As to the few hyperbolic orbits, in nearly

all the cases which are capable of complete investigation, it has been found that planetary

TABLE 1

NUMBER OF RECORDED COMETS

TIME INTERVAL	NUMBER OF COMETS		
	H	C	N-E
To 1 B.C.	53	81	—
1 to 100 A.D.	21	22	22
100 to 200 A.D.	18	22	23
200 to 300 A.D.	35	39	44
300 to 400 A.D.	21	22	27
400 to 500 A.D.	19	19	16
500 to 600 A.D.	24	26	25
600 to 700 A.D.	21	33	22
700 to 800 A.D.	13	17	16
800 to 900 A.D.	31	41	42
900 to 1000 A.D.	20	30	26
1000 to 1100 A.D.	28	38	36
1100 to 1200 A.D.	22	31	26
1200 to 1300 A.D.	25	30	26
1300 to 1400 A.D.	31	34	29
1400 to 1500 A.D.	35	45	27
1500 to 1600 A.D.	38	40	31
1600 to 1700 A.D.	27	35	12(b)
1700 to 1800 A.D.	96	73	36(b)
1800 to 1900 A.D.	(284)(a)	335	
Total		1056	

Note: In the above table the authorities are as follows:
H = Herz in *Handwörterbuch der Astr.*, Vol. II, 53, 1898.
C = Chambers in *The Story of the Comets*, 244, 1910.
N-E = Newcomb-Engelmann's *Astronomie*, 440, 1922.
(a) = To 1895 inclusive only.
(b) = Included only naked eye comets.

perturbations were responsible for the slightly increased velocity.[3] Allowing for these, the orbit is seen to be the usual parabola or very long ellipse.[4]

While all the large planets, and most of the asteroids, have orbits but little inclined to the plane of the ecliptic and they all move with direct, i.e., counter-clockwise motion, this is not true for comets. Omitting the short period comets of Jupiter's family, the rest are about equally divided between direct and retrograde motion, while their orbits have all possible inclinations.

To make the above statements clearer, a few statistics will be given (see table 1). Holetschek gives the perihelion distances of 409 comets up to 1917 as follows:

0.00 to 0.49	92
0.50 to 0.99	173
1.00 to 1.49	94
> 1.50	50
	409

[3] *Pub. A.S.P.*, 23, 124, 1911. Also, Newcomb-Engelmann, *Astr. Pop.*, 441, 1922.

[4] The recently published orbit of Comet 1926 VII, according to Crommelin, has an eccentricity of 1.008658. This excess over unity (i.e., the parabola) is too great to be attributed to errors of observation.

To *show that* with better observations few comets have parabolic orbits:[5]

Before 1755..........	99 per cent were computed as parabolic
1756 to 1845..........	74 per cent were computed as parabolic
1846 to 1895..........	54 per cent were computed as parabolic
Comets visible	
1 to 99 days.......	68 per cent were computed as parabolic
100 to 239 days.......	55 per cent were computed as parabolic
240 to 511 days.......	13 per cent were computed as parabolic

COMET MASSES

An excellent example of the changes wrought on a comet's orbit by a planet, with no appreciable reciprocal action, which fact proves the very small mass of the comet, is furnished by Lexell's Comet of 1770. Exact

[5] L. Rodés, S. J., *El Firmamento*, 303, 1927.

Those specially interested in the statistics of the elements of the orbits of comets should consult "Comet Catalogue" by A. C. D. Crommelin in *Memoirs of the British Astronomical Association*, Vol. 26, Part 2. This contains 561 orbits, but in some cases several refer to the same comet, as the catalogue aims to give the fullest information for each return of periodic comets. This publication is a sequel to J. G. Galle's Cometenbahnen, 1894, which contains orbits of 411 comets up to 1894.

calculation showed that it was very near Jupiter in 1767 and by the attraction of the planet had its orbit changed to one of small eccentricity and 5½-year period. Again in 1779 it came very near Jupiter, in fact passing actually through its satellite system. But the periods of the satellites were not at all changed, so far as observations could show. This meant that the comet had a mass less than $\frac{1}{5000}$ that of the Earth. This time its eccentricity was immensely increased, as well as its period, so that the comet has never been seen since. Incidentally in 1770 this same comet passed near the Earth and had its period shortened by 2½ days as a consequence. It came within about 1½ million miles; but the length of the year did not vary one second. Russell states that had the comet's mass been $\frac{1}{18000}$ that of the Earth a change of at least this amount in the length of the year would have resulted.[6]

Similarly Brooks's Comet in 1886 by nearing Jupiter too closely had its period changed from 29 to 7 years. In 1889 the comet was observed by Barnard at Lick Observatory to be double, the two parts separating at a rate

[6] *Astronomy*, 430, 1926

that would indicate that the disruption had occurred three years earlier, when it was so near Jupiter.[7]

But as the Earth weights 6.59×10^{21} tons, should a comet weight only one-millionth as much, it would weigh 6.59×10^{15} tons. If one-millionth of this still it would weigh 6.59×10^{9} tons—a very tremendous weight according to terrestrial standards. Yet neither of these hypothetical masses would produce observable perturbations. All we can honestly say, therefore, is that comets' masses are too small to produce observable effects by which they could be evaluated. But in no case can it be asserted that their masses are not large compared with that of terrestrial objects. The statement made by a prominent astronomer about a century ago "that a comet could be packed in a portmanteau," and one met with in certain books that collision with a comet would produce no harmful results to the Earth, are both so absurd that they do not deserve serious discussion (see p. 193).

Sometimes it is found that perturbations suffered by a comet as it passes a planet on one

[7] Young, *General Astr.*, 454, 1904.

occasion may later be reversed. An excellent case[8] in point is furnished by Wolf's Comet. Briefly, in 1875 this comet was so perturbed by a close approach to Jupiter that the inclination of its orbit was changed from 29.4° to 27.5° and its period from 8.53 to 6.82 years. Until 1922 it continued in an orbit essentially the same, but between July and December of that year it was again very near Jupiter. The result was that on leaving its sphere of activity the comet's orbit had an inclination of 29.1° and a period of 8.28 years, in other words its new orbit was almost the same as that followed in 1875.

The coma of a comet, paradoxically, always contracts on nearing the Sun, and expands as it recedes. The tail, on the contrary, develops in length the closer the comet approaches the Sun.

The condition of the coma of a comet, as the body nears perihelion, has long been a difficult point to explain. Any theory, which has the least probability, therefore, would be of a certain value. In view of this fact, some ideas bearing upon this question will now be

[8] *A. J.*, 34, 133, 1922.

outlined, though it is at once added that they are applicable directly to comets which have tails. If comets of short period, without tails, be included in the discussion, modification will be necessary.

To take a concrete case for illustration, Halley's Comet at its last return will be

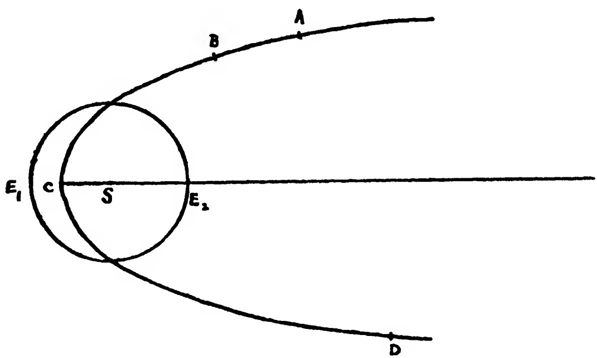


Fig. 1

chosen. It was discovered at 3 units distance from the Sun (position A) being then 14,000 miles in diameter. At 2 units distance (position B) it had grown to 220,000 miles. But at perihelion, when at distance 0.6 units (position C), it had contracted to a diameter of 120,000 miles. On the return journey back from perihelion, it first ex-

panded very considerably—in fact to even larger dimensions than it had as it approached—and finally disappeared at 4 units distance (position D), when it was 30,000 miles in diameter.

Following the usual theory, the comet at A is supposed to have just begun the development of its coma by gas oozing from the solid meteorites of the nucleus, under the warming influence of the Sun. This gas carries fine dust with it. The gas and dust diffuse outward in all directions, and so the coma expands. The dust reflects the sunlight, but the gases absorbing solar energy begin themselves to shine. As the activity increases, the finer particles are driven backward to form the tail, which latter is lacking at first and is most developed at or just after perihelion passage. So far nothing has been added to what is generally accepted, but here we will use another viewpoint. Let the position B be that at which the coma has its maximum diameter, the tail as yet having scarcely begun to form, or at any rate being very small. Then this may be considered that critical point at which a balance is reached, giving a maximum diameter to the coma which is subject simul-

taneously to the inherent forces tending to enlarge it and the depleting effects of the radiation pressure from the Sun. Up to B the former are the greater, afterwards the latter. In other words while indeed the further approach to the Sun may cause increased activity in the nucleus, yet this extra material is driven away more rapidly as the radiation pressure becomes more effective.

Thus from B to C the finer material, which must always have formed the outer shells of the coma, is being driven backwards into the tail faster than it can be supplied from within. Hence the coma actually would contract until perihelion is reached. Meantime the tail would increase in length and content. Both of these phenomena are generally observed in bright comets.

On the return journey, we would find the inverse order, only the maximum development would come after perihelion, due to the lag in the heating effects of the Sun. Just as our hottest days of summer come after and not at the summer solstice. As a further consequence, we would expect at any given distance from the Sun a greater activity on the return journey, for the comet is still using the

stored up energy just gained by its close approach. Also somewhat larger particles would now have been pried loose from the meteorites in the nucleus by the accumulated energy, and so a larger coma would be expected. Because, at a given distance from the Sun, larger particles would now form the outer shells of the coma. Hence there would be less susceptibility to radiation pressure and a larger coma would result. As the comet went still farther out, the activity of the nucleus would decrease correspondingly, until the comet would be too faint to be longer seen. Nevertheless we would expect a somewhat larger size up to the very last at corresponding distances, than when it was on its inward journey.

The above theory appears to fit fairly well the case of the average bright comet. If it be applied to one like Encke's Comet, here indeed is found the contraction of the coma, but practically no tail. Also these comets are absolutely fainter than the class first considered. With more hesitation it is suggested that the coma is depleted in exactly the same way as before, when the body nears perihelion, but the sum total of what is driven out is not

sufficient to form a visible tail, at least in most cases. If this general idea can be accepted as accounting for the contraction of the coma, at least we will be relieved from postulating unknown causes for this so far unexplained phenomenon.

The question of jets and other similar explosive changes in nuclei has been deliberately ignored here, because such phenomena are apparently additional to those by which the average coma is normally developed. The development of envelopes would seem to occupy a middle position between slow, normal development of the coma and violent changes. In their case it would seem that the forces had to accumulate a certain amount of energy in the nucleus, and then a greater amount of material was emitted at one time for their formation.

As to the transparency of the heads of comets, the following statements will be of interest. Struve[9] speaking of Halley's Comet on September 24, 1835 says: "At Dorpat the star was in conjunction only 2.2″ from the brightest part of the comet. The star re-

[9] *Cosmos*, 1, 89.

mained continually visible, and its light was not perceptibly diminished whilst the nucleus of the comet seemed to be almost extinguished before the radiance of the small star of the ninth or tenth magnitude."

Bessel[10] on September 29, 1835, saw a 10 magnitude star at 7.8″ from the nucleus of Halley's Comet, therefore, in very dense nebulous matter. The star's light experienced no deflection from refraction.

Van Biesbroeck,[11] at Yerkes Observatory, on June 22, 1927, took a photograph of a field of stars, with the 40-inch refractor, right through the head of Pons-Winnecke's Comet. He found 73 stars of about 12 and 13 magnitude on the plate, whose area was 35′ by 35′. The same region was again photographed when the comet had passed on. No indication of shifting of the stars could be detected, due to their light having passed through the coma, which was at least 100,000 miles thick. Any shift as great as 0.1″ could certainly, and one of 0.05″ could probably have been found.

The ancients[12] were struck by the phenom-

[10] *Astr. Nach.*, 288, 303, 1836.
[11] *Cosmos*, 1, 90.
[12] *Pop. Astr.*, 35, 499, 1927.

enon that it was possible to see through comets as through a flame. The earliest evidence is that of Democritus. Seneca says: "We may see stars through a comet as through a cloud, but we can only see through the rays of the tail, and not through the body of the comet itself."

Comets are discovered in a variety of ways, some by accident, others by persons who make a business of comet hunting. At present, some comets are picked up on developed plates when the observer had been photographing a region of the sky for a totally different purpose. Some are first seen by persons not at all interested in astronomy, as happened in the case of a bright comet not many years ago, discovered by railroad workers in South Africa.

Certain men stand out most prominently as being particularly successful in finding comets. Pons is credited with no less than 37 between 1801 and 1827; he was then doorkeeper at the Marseilles Observatory. Two other Frenchmen during the late eighteenth century were also particularly lucky, Messier and Montaigne. The following story told of the former will illustrate what a passion comet

hunting had become with him. It is a quotation from La Harpe:[13] "He is a very worthy man, with the simplicity of a baby. Some years ago he lost his wife, and his attention to her prevented him from discovering a comet he was then on the search for, and which Montaigne of Limoges got away from him. He was in despair. When he was condoled with on the loss he had met, he replied, with his head full of the comet, 'Oh, dear, to think that when I had discovered twelve, this Montaigne should have got my thirteenth,' and his eyes filled with tears, till, remembering what it was he ought to be weeping for, he moaned, 'Oh, my poor wife,' but went on crying for his comet."

During the past fifty years, Brooks, Barnard, Perrine and Swift in America, and Giacobini of Nice have discovered between 10 and 20 comets each. The discovery of 5 comets by Barnard, while he was at Nashville, Tennessee, and just starting his great astronomical career, helped him through a critical period of his life. In those days H. H. Warner offered a prize of $200 to a person

[13] Abbot, *The Earth and The Stars*, 87, 1926.

discovering a new comet—a reward alas no longer available! Gaining these five prizes largely enabled Barnard to pay for his home, which was afterwards known as "Comet House" to commemorate this fact.

The writer frequently has heard a story about a prominent astronomer which is worth telling, though he does not personally vouch for its accuracy. This man, who was an assiduous observer, was measuring a certain comet every morning just before dawn. As usual the comet was measured on a certain date, but on reduction the place was 1° off from where it should have been. Next morning a search showed two comets! The observer had discovered an entirely new comet because he had made an error of 1° in setting his declination circle the morning before. In view of this, it would be hard to prove that errors, even in scientific work, never have any value!

CHAPTER III

Comet Groups

By definition a comet group is composed of at least two comets, which, while obviously not the same body, yet move in practically the same orbit. The most famous of such groups is composed of the great comets 1668, 1843, 1880, 1882, and 1887. As no one of the last four, no matter how much allowance is made for errors of observation, could be returns of the same body, that possibility is at once ruled out. The elements of these five comets are given in table 2.

A glance at these figures (table 2) shows at once that all these comets passed within from 78,000 to 288,000 miles of the Sun's surface. They therefore passed directly through the solar corona. This means that the focus is almost at the very end of the ellipse, which is therefore excessively narrow and long. Indeed the comets came toward the Sun and retired therefrom in almost straight lines. Coming so near, they made the turn through 180° of heliocentric longitude in a few hours. However, when so close in they were subjected

to most terrific heat and radiation pressure, which—at least for the 1882 comet—split the nucleus and in all cases caused the development of extremely long, straight tails.

The comet of 1843 was not discovered until the day after perihelion passage which was later computed to have been on February 27, 1843, at $10^h\ 29^m$ Paris M.T. It was first seen

TABLE 2

ELEMENTS OF THE GREAT COMETS OF 1668, 1843, 1880, 1882, AND 1887

COMET	q	e	i	Ω	π	PERIOD
1668	0 0047	1 0	36°	357°	277°	?
1843	0.0055	0 99989	36	1	279	
1880 I	0 0059	0 99947	37	356	278	
1882 III	0 0082	0 99993	38	346	276	
1887 I	0 0054	1 0	43	337	274	?

in full sunshine on February 28, $1\frac{1}{2}°$ east of the Sun's center and with a tail 4° to 5° long. In a day's time it described 292° of its orbit, leaving only 68° for the hundreds of years before its return. At perihelion its velocity was 342 miles/sec.

The following observations of its appearance are quoted.[1] "On March 6 about seven

[1] *Silliman's Jr.*, I, 44, 414, 1843.

o'clock it presented a long, narrow brilliant beam slightly convex upward, the lower end being apparently below the horizon (it extended above horizon 30°); the breadth was about 2° at upper extremity and less than 1° where it was lost in vapors of horizon." "On March 7 it extended 43°. Its breadth near the horizon was less than 1°, and generally increased towards the upper extremity, where it may have been equal to 2½°. The curvature of the train upwards, although very noticeable, scarcely exceeded 2°. The light was nearly uniform." "On March 17 the comet shone with great brilliance; the curvature of train was less; its length was 34°. It was last seen here (New Haven, Conn.) by the naked eye on April 3, when (due to Moon) it was barely discernible."

A ship's captain, near the equator, saw its tail 69° long on March 4. General Ewart, who was on shipboard near St. Helena, says: "It was a grand and wonderful sight, for the comet now extended the extraordinary distance of one-third of the heavens, the nucleus being, perhaps, about the size of the planet Venus."[2]

[2] Chambers, 142.

The comet of 1880 (I), was discovered on February 1 at several places in the Southern Hemisphere. It passed perihelion four days before, and was visible about three weeks in all, being unfavorably placed for observation. Gould at Cordoba stated that at no time was there a nucleus, the head appearing cloud-like and filmy, and elongated in the direction of the tail, which it did not much surpass in brightness. A tail 40° long, and from 1½° to 2½° wide, was seen on February 7, but its brightness was not superior to that of the Milky Way in Taurus. On February 4 it had a coma 2′ to 3′ in diameter.

Comet 1882 (III) was one of the finest on record, and, as it was observed for nine months, the orbit was excellently determined, and all its phenomena studied in great detail. This comet was seen first as a naked-eye object on September 3, in New Zealand. In four days it had become so conspicuous that it was visible at noonday near the Sun on September 16. It transited the Sun on September 17. The comet was traced right up to the Sun's limb by Elkin and Finlay at the Cape of Good Hope, where it disappeared as suddenly and effectively as a star occulted by the Moon.

The nucleus was then 5″ in diameter, but no trace of it could be seen on the solar disc.[3] It was visible for two days afterwards in full sunlight. Its perihelion occurred on September 17, when later on the same day it could be seen within 2° of the Sun. Because of its small perihelion distance, it, like the rest of this group, passed through the corona.

The changes in the head of this comet were so great and remarkable that Young's words[4] will be quoted, he having himself been a most able observer: "When the comet first became telescopically observable in the morning sky it presented a very nearly normal appearance. The nucleus was sensibly circular, and there were a number of clearly developed concentric envelopes in the head; the dark, shadow-like stripe behind the nucleus was also well marked. In a few days the nucleus became elongated and finally stretched out into a lengthened, luminous streak some 50,000 miles in extent, upon which there were six or eight star-like knots of condensation. The largest and brightest of these knots was the third from

[3] Certain observations, claimed to have been made of this transit, have been generally considered most doubtful.

[4] *General Astr.*, 459–60, 1904.

the forward end of the line, and was some 5,000 miles in diameter. This 'string of pearls' continued to lengthen as long as the comet was visible, until at last the length exceeded 100,000 miles."

The changes began to be noted about October, and were seen by many observers, so there is no doubt of their reality. A further proof of disruption was one or more masses or shreds of cometary matter, perhaps 3° distant, that were seen, by at least three astronomers in different places and on different nights, to be accompanying the main comet. The one noted by Schmidt at Athens, on October 9, was seen on several subsequent days. Its orbit proved to be quite similar to that of the main comet.

Russell's remarks[5] will help us to understand why abnormal behavior might have been expected after such a near perihelion passage: "The great comet of 1882 passed, at perihelion, through a region where it was about 3000°. Its nucleus, which survived the passage though breaking into four parts, must have been composed of masses of considerable

[5] *Astroph. Jr.*, 69, 54, 1929.

size. As this comet is undoubtedly periodic, it must have been stripped of all finer material at earlier returns, and is probably far from typical of other comets." It seems that we should add other comets "whose perihelia are not equally near the Sun."

Due to the relative position of Earth and the comet, its tail, though quite 100 million miles in actual length, never subtended an angle of more than 35°. It fell under Brédikhine's second or hydrocarbon type (Young). Tempel suggested that the tail was tubular in form, while a drawing by Hopkins on November 14 shows the wider end bifurcated. Holden's drawings show three nuclei on October 13 and 17, while Cruls saw two on October 15. The latter suggested that these nuclei, 7 and 8 magnitude respectively, each had a tail, and that the curious appearance of the one tail was due to there being really two superimposed.

Besides the phenomena mentioned, the comet also had a sheath of light that enveloped the head and extended 3° or 4° in front of it. This was faint and straight-edged.

As for the period, before the nucleus divided, it was calculated to be 800 to 1000

years. Kreutz calculated the periods of each of the four nuclei into which the original broke up. These turned out to be 664, 769, 875 and 959 years. We will probably see four comets of lesser magnitude return about the years 2546, 2651, 2757, and 2841 A.D., in place of the one great body as in 1882.

As for its spectra, when very near the Sun the sodium D lines showed very bright, also the E and some other iron lines were reported bright, as well as five unidentified lines in the red. On September 18, the radial velocity of the comet was determined at both Dun Echt and Nice, the results agreeing well with the calculated velocity. As the comet receded the bright lines faded, the D lines lasting longest, and the carbon bands came into greater prominence.

It should, however, be stated that the identification of the iron lines mentioned has more recently been gravely questioned. Indeed before the days of photography the identification of lines by visual methods was most difficult, and errors were to be expected.

Comet 1882 (III), for which there were so many observations, was used by Hufnagel[6] to

[6] *Bul. Astr. Soc. de France*, **34**, 390, 1920.

see if an orbit calculated on Newton's Law, or that on Einstein's theory, would best fit the facts. But the observations fitted one as well as the other; hence no choice could be made. As the comet came within 0.67 radius of the Sun's surface, and was moving at 478 km/sec, he concluded that there was no trace of a resisting medium and that the zodiacal light could not be made up of ellipsoids of density increasing as the Sun is approached.

Another small comet that was discovered within less than 1° of the Sun on a plate taken during the total solar eclipse of May 17, 1882, very probably belonged to this same group.

The comet of 1887 belonging to this group was discovered by Thome at Cordoba, on January 18. It was observed five days later at Melbourne. The comet was readily visible to the eye in the strong twilight, the tail being long, straight, and narrow.

Part of the description by Tebbutt will be quoted: "Its position was on the southwest horizon (January 20), but nothing could be seen of the nucleus (January 28), the tail could be faintly seen extending over many degrees, and I noticed at its lower or brighter extremity a star, which I took for the nucleus.

On pointing the $4\frac{1}{4}$-inch equatorial I saw the supposed nucleus was really a fixed star. Although the lower extremity of the cometary ray or beam was certainly in the immediate neighborhood of this star I could not find the slightest condensation. The tail was straight." (January 30) "My search for a nucleus or even the slightest condensation as a point of observation was again quite unsuccessful, (February 1) not the slightest trace of the tail could be seen owing to the brilliancy of the Moon."[7]

In fact never did this strange object have any condensation in the head, which made its orbit depend upon uncertain observations. It passed perihelion January 11, and the length of its tail shortly after discovery was nearly 40°. We might well wonder whether a similar object, which did not approach nearer than 0.5 unit of the Sun, would ever be visible at all?

[7] *Observatory*, 10, 66–7, 1887.

CHAPTER IV

Comet Families

In practically all textbooks written ten or more years ago, the statement is made that the four major planets of our Solar System each has a family of comets. The idea was that when the aphelion distance of a comet happened to be about the same as the radius of a planet's orbit, then at some distant epoch comet and planet passed near each other and the latter changed the original orbit of the comet into a smaller one. At the next passage, the period might be still further shortened, and so on until eventually the comet's aphelion point was drawn close to the planet's orbit. When this had been accomplished, the comet was said to belong to the planet's family.

Russell,[1] however, pointed out that on this basis of "capture" Jupiter must have done practically all the capturing. He states that only one out of the three comets assigned to Saturn and the two assigned to Uranus comes

[1] *A. J.*, 23, 49, 1920.

within 50,000,000 miles of either planet's orbit. As for the eight assigned to Neptune, none comes closer than nearly four astronomical units of its orbit! Everyone of these latter will probably come actually closer to Jupiter's orbit than to that of Neptune. The only possible answer to this argument seems to be that supposing Neptune originally "captured" these eight comets, for instance, on later returns, as the comets approached the Sun, they underwent further perturbation from the other planets, which so shifted their orbits that the present state of things came about. However, the objection does not seem a strong one, and it would be wiser to give Jupiter the major credit. Again the chance that a comet will pass within a given distance of Jupiter's orbit to that that the comet would pass to within the same distance of Neptune's is about 33 : 1; the chance that it will pass within a given distance of the respective planets themselves is about 460:1. On the contrary, once a comet is within a certain distance of Neptune, it will remain longer as both Neptune and it will move more slowly than would Jupiter and the same comet were they passing. This velocity ratio, however, is only

2.4 : 1, so dividing this into the 460, it still leaves the chances not far from 200 : 1.

Ruling out, therefore, the families of Saturn, Uranus, and Neptune as being probably only apparent, we are left with the large and growing family of Jupiter alone to consider. We say growing because new comets are constantly found which fulfill the conditions. But this is not the whole picture for cometary "death" or at least disappearance has robbed Jupiter of a few of its children, notably Biela's Comet of famous memory.

In addition to having their perihelia near Jupiter's orbit, a common characteristic of these comets is low inclination for their orbits and direct motion. Their periods must be < 12 years from Kepler's Third Law as the length of the major axes of their orbits cannot exceed that of Jupiter's. None of them is a conspicuous object, though several have been visible to the naked eye at times. Some of them have little or no tail, even near perihelion. These latter characteristics may be most readily explained on the fact that their short periods force them to return every few years to the vicinity of the Sun. The latter then has gradually depleted these comets of

tail forming material until little or none is left, and also the various forces of disintegration, explained elsewhere, due to both Sun and planets work upon them more continuously and effectively than on comets of long period. We shall take up briefly the description of a few of these comets, however, confining our attention in this chapter to Encke's Comet only.

Encke's Comet belongs to Jupiter's family and has the distinction of being that with the shortest period known. It is never a bright object, so it is due to the above fact, and to certain peculiarities of its motion, that much attention has been paid to this inconspicuous comet.

The first time this object was seen was on January 17, 1786, when a telescopic comet was discovered by Mechain at Paris. It was fairly large, with a bright nucleus, but no tail. It was noted on only three nights, though seen by other observers. Naturally an orbit, based on such a short arc, was most approximate.

The object was next discovered by the most famous of female astronomers, Miss Caroline Herschel, on November 7, 1795. It was then about 5′ in diameter and had no nucleus. It

was visible three weeks this time, but its motion could not be satisfied at all by a parabolic orbit. The third discovery was ten years later, when it was found by Thulis on October 19, 1805. On November 1 a 3° tail was visible. Again the object was seen for three weeks. This time an elliptical orbit, calculated by Encke, gave a period of 12.12 years, making it one of the shortest periods then known.

Thirteen years later, Pons at Marseilles, who has so many comet discoveries to his credit, found a faint telescopic comet on November 26, 1818. This time the comet remained under observation for seven weeks. Encke undertook a rigorous calculation of the orbit using the new Gaussian method. This at once gave an elliptical path, the period of the comet being about three and one-half years. He was now suspicious that the 1818 comet was a return of the one in 1805, as the elements were very similar. Further research made him certain that not only had the 1818 comet been observed in 1805, but also in 1795 and 1786. He was not the only one to perceive these connections, as Arago in France announced it independently for the 1805

Comet, and Olbers in Germany extended it to the two earlier cases.

Nevertheless, to Encke properly goes the great credit, and his important work on the comet has been universally recognized by the naming of the object after him. While other astronomers made suppositions, he calculated the perturbations of the object for the three earlier returns, proving definitely that the same comet had been seen four times. He next computed an ephemeris for the return in 1822, which took place on May 23. He showed that Jupiter's perturbations would lengthen the comet's period nine days, and that it would be visible only in the Southern Hemisphere. This prediction was brilliantly fulfilled by its discovery on June 2, 1822, by Rümker at Parametta, in Australia, who followed it for three weeks.

One would think that this comet had almost a habit of staying in view from the Earth exactly this period of time! Encke was now able to predict a perihelion passage for September 16, 1825. This time the comet was discovered as early as July 13, and was followed for eight weeks. During this return it was described as a faint nebulosity about

$1\frac{1}{2}°$ in diameter. Its next perihelion passage was on January 9, 1829, but it was discovered on October 23, 1828. Six weeks later it was easily visible to the eye as an object of 5 magnitude.

TABLE 3

ABRIDGED-FORM OF ENCKE'S CALCULATIONS

RETURN	PERIOD	RETURN	PERIOD
year	*days*	*year*	*days*
1786		1822	
	1212 7		1211.55
1789		1825	
	1212 67		1211.44
1792		1829	
	1212.55		1211 32
1795		1832	
	1212 44		1211.22
1799		1835	
	1212 33		1211.11
1802		1838	
	1212 22		1210.98
1805		1842	
	1212.10		1210 88
1809		1845	
	1212 00		1210.77
1812		1848	
	1211.89		1210.65
1815		1852	
	1211.78		1210.55
1819		1855	
	1211.67		1210.44
1822		1858	

The comet was observed in 1832, 1835 and 1838. On this last return it was discovered on August 14, perihelion passage being on December 19. This time it remained under observation for the long period of sixteen weeks. It was due to this return that the announcement was made by Encke that, even after every

possible planetary perturbation had been allowed for, the comet returned each time to perihelion two and one-half hours too soon. Table 3 is abridged from one calculated by Encke.[2] Allowances are made for planetary perturbations.

The only possible explanation seemed to be that the body traversed a resisting medium which, according to the well-known paradox, will cause an increase of the velocity and hence a shortening of the period. On the basis of this, the "resisting medium" was rather widely believed in about the middle of the nineteenth century. But the curious fact remained that other comets, with a possible exception or two, showed no such acceleration. Further, more recent work by Backlund, who had the advantage of the numerous observations of many subsequent returns, proved that the resistance to the motion had decreased, apparently almost abruptly in 1858, 1868, 1895 and 1904. He also showed that the retardation seems to occur in a relatively narrow sector of the orbit near perihelion. It mounted to an augmention of 0.1″ to the daily

[2] *Mon. Notices*, R. A. S., 19, 7, 1858.

motion during 1819–1859, but to only 0.01″ during 1904–1908.

Nevertheless from 1819 to 1927 the total diminution of period amounted to nearly three days, the mean distance decreasing as a consequence by nearly 300,000 miles. If such an effect kept up indefinitely we might expect the comet to finally spiral into the Sun. Though today we no longer believe in a general "resisting medium," it seems necessary to postulate some resistance. Perhaps the best we can do is to assume that the critical part of the comet's orbit intersects a region very rich in meteoric material, which, if dense enough, would produce such an effect. An alternate hypothesis is that some physical alteration has taken place in the comet itself. The writer would incline to the first explanation as being more probable.

This comet, whose recent history is so well-known, illustrates splendidly the changes that take place in the coma of such objects. A few figures will illustrate this point. On October 28, 1828, when 135,000,000 miles from the Sun, its diameter was 312,000 miles; on December 24, 1828, perihelion passage being sixteen days later, it was only 14,000 miles.

At perihelion in 1838, when 32,000,000 miles from the Sun, the diameter was only 3000 miles. The dimensions for this return will be quoted at length as typical[3] (see table 4).

The last return of Encke's Comet was in 1927, when van Biesbroeck found the comet

TABLE 4

DIMENSIONS OF ENCKE'S COMET IN RETURN OF 1838

DATE	R	DIAMETER
1838		*miles*
October 9	1.42	278,000
October 25	1.19	119,000
November 6	1.00	80,000
November 13	0.88	75,000
November 16	0.83	62,000
November 20	0.76	55,000
November 23	0.71	37,000
December 12	0.39	6,500
December 14	0.36	5,500
December 16	0.35	4,200
December 17	0.34	3,000

on November 13, its magnitude being 16.0. He later found images of it on plates of October 19 and 20, when its magnitude was 17. On December 21 it had risen to 12 magnitude. On January 21, 1928, the comet had a sharp nucleus, with a broad tail 5′ long.

[3] Guillemin, *World of Comets*, 242, 1877.

The total light equaled magnitude 8. By February 1, it had risen to magnitude 6; the coma was 2′ in diameter and round, there was a nearly stellar nucleus, not in the exact center. The perihelion passage took place on February 19. According to Crommelin, there was no trace of an acceleration on this last return.[4] The comet was still observable from the Southern Hemisphere during March.

The statement is met with that Encke's Comet is about as bright as when first seen, but a very complete study by Vsechsviatsky[5] showed that the rate of decomposition of the comet amounted to one magnitude per century. Obviously in a few centuries it must become wholly invisible, if his conclusions are true.

The comet has been missed at no return since 1819, the last being the thirty-seventh return which was observed.

[4] *Observatory*, 51, 137, 1928.

[5] *Russian Astr. Jour.*, 4, 298, 1927.

CHAPTER V

The Tails of Comets

"All as a blazing starre doth farre outcast
His heavie beames, and flaming lockes dispelled,
At sight whereof the people stand aghast"
—Spenser.

With two known exceptions, a nebula and an M-type giant star, the tail of a great comet is the most bulky thing in the universe. Despite this immense volume, its mass is very small; so small indeed that only semi-intelligent guesses can be made as to what it is. Yet it is one of the most beautiful and interesting phenomena to be found in the whole realm of astronomy.

All comets do not have tails; in fact a tail is an appendage ~~which, with~~ the brighter comets, grows and develops only in the neighborhood of the Sun. It is probable, if not certain, that in the zone of the outermost planets no comet has one. Some of the smaller and less conspicuous comets appear to have none at any time, or at best very short and faint tails.

In examining a comet visually, or the

photographs of one, it is not possible to draw an absolutely sharp limit and say that here the coma ends, there the tail begins. For the tail extends out from the coma, but where they join there is an inevitable blending of their light. The most striking fact is, however, that the tails of all comets point, in general, away from the Sun. Hence as the comet approaches perihelion, the tail streams after, like the smoke from a moving vessel. But after perihelion, when the comet is leaving the Sun, the tail goes first.

The dimensions of tails will be discussed for specific comets in detail; here it suffices to say that in certain cases they have been known to be from 50 to 150 million miles long, when at their greatest development, and, at the end away from the Sun, to be from 5 to 10 million miles across. Certain phenomena lead us to think that they have more or less the structure of a flat, curved, hollow cone; i.e., that there is more material in or very near their apparent boundaries than there is inside. The word fan-shaped is often appropriately used to describe certain types.

It is evident that the material which forms a comet's tail must come from the coma.

And further that such material is acted upon by a repulsive force or forces whose seat is in the Sun. Consequently any particle in the tail must be subject to at least two forces; the gravitation of the Sun which produces an acceleration toward that body; and the repulsive force which tends to drive the particle away. Hence its actual motion at any instant is the vector sum of these two. Observation proves that the repulsive force is greater. This means further that the tail material is lost by a comet, and will never be regained. So unless a comet is furnished in some obscure way with a fresh supply it is only a question of time before its tail material will be used up. All evidence is that there is no compensating gain, at least of any equivalent amount, so that such material must be lost on every perihelion passage.

In some comets, which evidence considerable activity, when near the Sun, jets and streamers of light or a series of envelopes are developed which are concentric. During these eruptions the nucleus charges continually in apparent size and brilliancy, usually growing smaller and brighter just before the liberation of each envelope. The

Brooks's Comet

Photographed by Barnard at Yerkes Observatory, October 19, 1911

ejection of a jet, however, seems to set up a sort of oscillation of the nucleus. These envelopes seem to be composed of particles, forming apparently sheets of light, which are expelled from the nucleus in arcs ranging from 180° to 270°. The center of the arc is generally in line with the axis of the tail. The mode of action seems to be that these particles are expelled from the nucleus, but, at a certain distance out, those toward the Sun are turned back by its repulsive force. The result is that they stream sideways on both sides, eventually getting back into the tail proper. With Donati's Comet of 1858 there were intervals of from four to seven days between the formation of envelopes. But with Morehouse's Comet of 1908, the envelopes lasted only a few hours and actually contracted as they grew older; (see page 166). Several were indeed visible at once. These envelopes seem not to be sections of the surface of spheres, but of paraboloids of revolution.

In Comet 1862 (II) according to drawings by Secchi, the envelope was complicated by two actual jets of matter which, expelled toward the Sun from the nucleus, were turned back in graceful curves, not unlike the jet

from a hose, held at a 60° angle with the ground.

From what has been said it seems that the Sun sets up activity in the nucleus of the comet, which leads the latter to expel par-

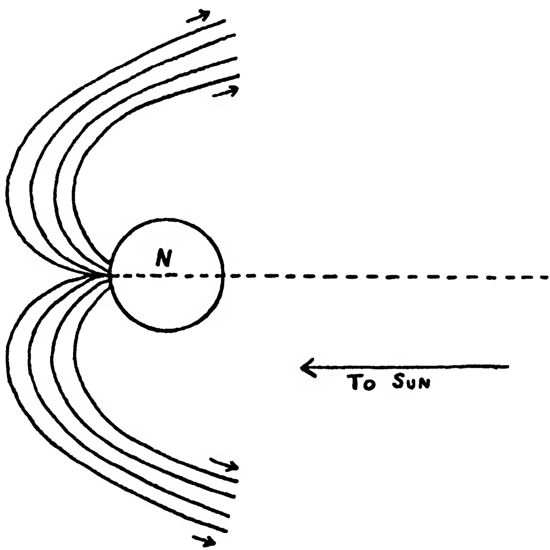


Fig. 2

ticles. Those of the latter, moving toward the Sun, are eventually turned back. Hence all, no matter in what direction they were originally expelled, go to form the tail. Figure 2 shows an ideal case. It should be added that

the sunward side of the nucleus is the one on which this activity is usually found.

We have said that the tail is opposite to the Sun. This is true, but there is always a lag with regard to the line Sun-comet. The angle made by the tail with this line varies for different comets, for the same comet on different dates, and sometimes we even find a comet having two or more distinct tails at once, making quite a large angle with one another. The curvature is practically entirely in the plane of the orbit. Therefore to an observer in this plane even a sharply curved tail appears straight.

The Russian astronomer, Brédikhine, set forth a theory, which though modified, has been the chief basis of our present opinions. From the study of forty or more comets, having one or more tails each, he came to the conclusion that three types of tails covered most cases. He assumed a repulsive force, acting inversely as the square of the distance, of an unknown character. But that while able to push back the very small particles which would form the tail, this force was too feeble to affect the motion of the head of the comet. This would lead us to infer a rather

hollow tail, which inference is often shown to be correct in that the middle of the tail, as we see it, is darker than the edges. His results are shown in table 5.

Brédikhine inferred further that the repulsive force was proportioned to the molecular weights of the tail particles. On this basis he thought type I to be of hydrogen,

TABLE 5

Tabulated Results of Brédikhine's Theory

TYPE	REPULSIVE FORCE ÷ SUN'S ATTRACTION	INITIAL VELOCITY
I	18	3.0 to 10.0 km/sec
II	0.5 to 2.2	0.9 to 2.0 km/sec
III	0.1 to 0.3	0.3 to 0.6 km/sec

type II of carbon, etc., type III probably of iron. In addition, for a few comets he found a repulsive force of 36; for these he assumed an unknown gas lighter than hydrogen, an assumption now wholly discredited. For anomalous tails, which sometimes point in the general direction of, rather than from the Sun, all we have to do is assume that the particles composing them are heavy enough for gravitation to predominate.

Historically, Kepler and later Euler suggested that the pressure of sunlight was the cause of comets' tails. Olbers in 1812, and then Bessel, brought in electrical forces, assuming Sun and comet had charges of the same sign. Later came the "cathode" ray theory, which was suggested by the spectroscope. According to this comets' tails are only streams of cathode rays sent out by the Sun. However, the preponderance of opinion now is that the principal agent is the radiation pressure of sunlight.

The existence of this force, so feeble for bodies of ordinary size, was proved by P. Lebedew in 1900, and independently by E. E. Nichols and G. F. Hull in 1901 by laboratory experiments. We should add that gravitation of course is proportional to the mass of the body in question, which in turn equals volume times density. Light pressure on the contrary, in the nature of the case, can be only proportioned to the area. For any body volume depends on the cube of a dimension, area upon the square. Let us now take a very small object, in the shape of a regular cube, with edge equal to a. Then $g \propto a^3$; $p \propto a^2$. Suppose this is of the critical size where g =

p exactly[1] then for a cube with edge $= \frac{a}{10}$, we find $g \propto \frac{a^3}{1000}$; $p \propto \frac{a^2}{100}$, obviously therefore if $g_0 = p_0$, $p = 10g$, or the light pressure is ten times as great as gravitation in the second case. On the contrary for a cube with edge $10a$, the opposite would be the case. For a spherical dust particle $\frac{1}{100,000}$ inch in diameter, $p = 10g$. We cannot push down the sizes of particles indefinitely, and, as we approach the size of a wave-length of light, Schwarzschild has shown that the pressure is a maximum for particles whose diameters equals $\lambda/3$, λ being wave-length of incident radiations. Bosler[2] says: "We might then believe that radiation pressure is not exercised upon gases whose molecules are scarcely 10^{-8} cm. in diameter, and therefore smaller than the limit above. However, gas gives place to a selective absorption which just compensates the inverse influence of diffraction and Lebedew has succeeded in showing by a very delicate experiment that light does exercise its pressure upon gaseous molecules. Only, due to the very feeble

[1] Equality of solar gravitation and light pressure exists for a sphere of diameter = 0.0015 mm.

[2] *Astrophysique*, 424, 1928.

absorbing power of gas (that is, its transparency) the force thus manifested is minimized, hardly indeed $\frac{1}{100}$ part of the corresponding force on solid particles. Again if it is a question of gas at atmospheric pressure and cometary matter, if the latter is gaseous, it is surely at very much lower pressure."

The discoveries of Debys and Lebedew leave unanswered the question as to whether comets' tails are formed of solid dust particles or gaseous molecules.

Fabry, discussing the probability of comets' tails being gaseous, calculated that a tail which was 160,000 miles thick and had a density of 10^{-11} (compared with air) would be plainly visible if it diffused light in the same way that skylight is diffused. But along with molecules of gas, there seems no doubt that dust particles must be mingled. Further, streams of particles, actually expelled from the Sun, may play a part.

Due to faintness, the spectra of tails are difficult to obtain. They show bands. These latter seem to be due to the third negative group of carbon and the negative group of nitrogen, at very low pressure.

We have seen that particles, which later

form the tails of comets, are driven away from the comets' heads by repulsive forces. Such a particle will move in a hyperbola but not in that branch which has the Sun for its interior focus. It must move in the other branch, convex to the Sun. In some tails there are knots or condensations which are sufficiently distinctive to be recognized on succeeding days. It has been possible therefore to measure their positions on different dates, and hence calculate their velocities. The result proves that they move faster as they leave the comets' heads. In recent years Morehouse's Comet in 1908 and also Halley's Comet furnished excellent examples. Such measures are difficult to make very accurate, due to the irregular and changeable shape of the knots. In the latter case Curtis found the velocities given in table 6 for various knots that he identified on successive days (distance in astronomical units). On May 31 the comet was 97 million miles distant from the Sun, and the tail averaged about 18 million miles long during the above interval.

However, Halley's Comet had a perihelion distance of 55×10^6 miles, while some comets, as for instance Comet 1843, had a perihelion

distance of only about 500,000 miles, passing actually within 78,000 miles of the Sun's surface. Naturally this meant tremendous activity in tail formation. This comet when nearest the Sun had a velocity of 330 miles/sec, and took only $2^h\ 11^m$ to go through 180°

TABLE 6

VELOCITIES FOUND BY CURTIS FOR VARIOUS KNOTS ON SUCCESSIVE DAYS

1910	DISTANCE FROM NUCLEUS	KM/SEC
May 12, 14	0 003	5
May 27–28	.004	13
May 25–26	.010	19
June 2–3	.015	32
May 31–June 1	.019	35
May 26–27	.027	38
June 6–7	.044	70
May 30–31	.071	71
June 7–8	.090	91

of its orbit. Its tail was 150 to 180 million miles long.[3] This means that, were the tail made up of relatively stationary particles, one at the end, (taking the lower estimate) would move through 47×10^7 miles in 141 minutes

[3] Flammarion, *Astr. Populaire*, 626, 1881.

or 56,000 miles/sec; a speed over one-fourth that of light. Bosler[4] remarks that this is only an illusion, as it was not the same matter which one perceived at the same distance out from the nucleus at successive instants. The reason given by him and many others is, inferentially, that such velocities are out of all reason. It seems to the writer that this often-repeated statement met with in texts has no sound basis for this reason: let, in figure 3,

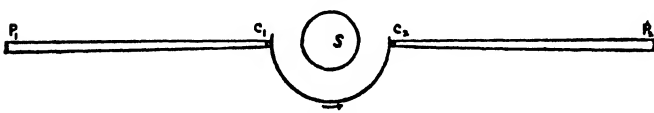


FIG. 3

C_1 and C_2 be positions of this comet, C_2 just after it has moved through an arc of 180° in 141 minutes. Let the tail $C_1 P_1$ be supposed equal in length to C_2P_2. Now it is geometrically evident that no particle, *already* repulsed at C_1 and which has gone an appreciable distance towards P_1 can possibly, by any juggling of construction, get into tail C_2P_2. Hence the *minimum* distance a particle at P_2 would have to travel, would be

[4] *Astrophysique*, 419, 1928.

along some curved path from C_1 to P_2. At a minimum this is $> C_1P_2$ in length. This proves that the average velocity of P_2 must have been $\frac{C_1P_2}{8460}$ or 18,000 miles/sec, which is only in the ratio of $1:\pi$ to the velocity which we would have were we to consider P_1 actually revolved around to P_2. While indeed three times smaller, it is a quantity of same order. It happens that this velocity is nearly that of the alpha rays, which consist of positively charged particles having a mass about four times that of the hydrogen atom.

It is obvious that the apparent length of a comet's tail as seen from the Earth is, in a given case, no indication of its real length. Also as stated its curvature, being almost wholly in the plane of its own orbit, is nearly always seen by us projected into a different shape. Tails are usually described as being transparent, that is stars seen through them lose no brightness. Yet Sir William Herschel assures us that, for the comet of 1807, stars seen through the tail lost some of their lustre, and one near the head was only faintly visible by glimpses.[5]

[5] Phil. Trans., xcviii, 153, 1808.

As typical of the mass of a tail take Halley's Comet. When the tail was long, Schwarzschild calculated that if it were composed of fine dust particles it might have a weight of 1 million tons, but if only of gas molecules then probably not over 100 tons. (Both constituents are probably actually present, but in what proportion is unknown.) He further calculated from the observations on its brightness that there could not have been more material in 2000 cubic miles of the tail than in 1 cubic inch of ordinary air, and possibly even less. The density of no artificial vacuum can come anywhere near being so low as this!

While it is certain the Earth must frequently, in ancient times, have plunged through tails of comets, without it being known or at least recorded, yet twice in the past century this has occurred; in 1861 and in 1910. The first case took place on June 30, just a day or so after the comet had become visible to astronomers in the northern hemisphere. No prediction of the event had been made but several persons in England including Hind[6] recorded a peculiar phosphor-

[6] Chambers, The Story of the Comets, 156, 1910.

escence or illumination of the sky. The writer knows of one man in America who observed the same thing, Dr. Milton W. Humphreys, afterwards professor of Greek at the University of Virginia, and one of the most brilliant scholars in the country. Though barely grown when he saw this phenomenon, at sunrise from the Virginian mountains, his keen interest in all science caused him to note the peculiar glow, which he had never before seen. Dr. Humphreys personally told the writer of this, saying that it was many years before he learned the explanation.

The second case was Halley's Comet on May 19, 1910. But this time we did not apparently go through the main tail, but through a detached streamer.

The writer, then at Lick Observatory, California, was awake and on the lookout all the previous night, as were most of the staff. However, brilliant moonlight effectually obscured unusual phenomena, if indeed there were any. The writer observed at intervals with the 12-inch refractor in the region of the computed radiant of any meteor that might come from the tail, but saw none. (He would like to add that in view of our present knowl-

edge the presence of meteors therein would be a most surprising phenomenon! He was not, even then, personally responsible for computing this radiant. The position was found in some journal.) However, this case was not comparable to that of 1861 when the main tail of the comet was doubtless completely passed through.

Of comets with several distinct tails perhaps that of 1744 holds the record with six, while the great Comet of 1825 comes a close second with five. It is true that Borelly's Comet of 1903 showed nine on a Greenwich photograph, but several were very faint.[7] The daylight comet 1910*a* for several nights showed two distinct ones, with very different curvatures, the longest being at least 30° in length. Biela's Comet had a companion with a tail or tails of its own. Late in February, 1846, it had three tails, a tripod tail as Maury expressed it (see p. 137). Many other cases could be quoted. It is, however, well to call attention to the fact that on photographs of bright comets the tail is not uniform all the way across, but often seems made up of

[7] *Mon. Not.*, R. A. S., 64, 84, 1903.

bright, long, streamers, with darker spaces between. To the writer the streamers as they approach the wider end, on some photographs of Halley's Comet, strongly remind him of auroral streamers in relative position and shape. According to Chambers[8] the following rather recent comets had a second tail, sometimes called a "beard" which reached out more or less toward the Sun: Comet of 1823, 1848 (II,) 1851 (IV), 1877 (II) and 1880 (VII). He further states, on the authority of Valz that the main tails of comets 1863 (IV) and (V) deviated from the planes of their orbits, and that only two other similar cases were known.

The question of "vibration" or "flickerings" that have been reported as going from end to end of certain tails at short intervals is doubtless purely a meteorological effect, and deserves no discussion here.

Comet Brooks (1911*c*) and Comet Gale (1912*a*) each furnished a chance to compare Brédikhine's theory with facts. According to Baldet's work, using an objective prism camera, the tail of the former could be traced

[8] Page 23.

5° from the nucleus. At this distance it still had almost the same intensity as near the head. Its spectra consisted of the third negative group of carbon. The negative group of nitrogen was absent. The more intense images were doubled on the plate of October 31. Also one could distinguish on this plate clearly two branches of the tail forming an angle of 25° with one another. And they gave the same spectra! According to the theory of Brédikhine the tails would be sensibly types I and II, attributed respectively to hydrogen and hydrocarbon.

Again Comet Gale had two principal tails, the one sensibly rectilinear, long and relatively intense, the other curved, feeble, short, forming with the first an angle which varied from 65° to 90°. These two tails belong to types I and III of Brédikhine, who assigned the first to hydrogen and the third to metallic vapors. But on the plate of October 17 can be seen the spectrum of the first tail having at its base, on the edge of the continuous spectrum of the nucleus, the very short image of the second tail about ⅓° long. The angle between the tails on the spectrogram is about 70°. Both tails have the same identical spectrum of the third negative group of carbon.

These two cases, cited by Baldet, seem to contradict decisively Brédikhine's theory of comets' tails so long held as most probable, unless indeed this were greatly modified. Bobrovnikoff states that Comet 1914 (V) had two tails, both showing the same spectrum. He further adds that no tail has ever shown the hydrogen or metallic (except sodium) spectrum.

In discussing Morehouse's Comet, Barnard makes the following remarks about the receding masses photographed in its tail.[9] "It would seem reasonable that these masses would have a much slower speed than the individual particles forming the general stream of the tail. They probably contain particles of greater size and mass which would be less under the influence of the pressure of sunlight, and would, therefore, have a much less outward velocity than the general particles of the tail. Whatever the cause, the fact is that on several occasions these masses have had independent streams or tails issuing from them, like those from the comet itself, where the smaller particles are evidently detached from

[9] *Astroph. Jr.*, 28, 289, 1908.

the mass and forced out with a very much greater velocity. This was also shown in the case of Daniel's Comet in July 11, 1907, when a mass left behind was actually moving sunward under the combined influence of gravitation and the initial velocity of its particles when component parts of the head. I have called attention to this peculiarity in the case of Borrelly's Comet, where the new tail of July 24, 1903, was moving out more rapidly than the rear portion of the old disconnected tail, which was at that time drifting away from the comet and Sun.

"An example of secondary tails from receding masses is found on a photograph of Swift's comet on April 7, 1892. Morehouse's Comet also presented a similar appearance on October 15."

Many further details will be given about the tails of various comets, discussed in other chapters, which need not be repeated here.

CHAPTER VI

THE SPECTRA OF COMETS

"A blazing star, which is thought by the ignorant to portend disaster to rulers. . . . ."

—SUETONIUS.

For a complex body like a comet, which undergoes extreme changes in its nearness to the Sun, the spectroscope would be expected to give important data. However, due to the faintness of many such objects, and the area over which their total light is always distributed, observations are difficult or impossible with certain types of spectroscopes. At present the short-focus prismatic camera is in high favor.

The oldest spectroscopic observation, known to the writer, was by Donati. At Florence on August 5, 1864, he observed Tempel's Comet 1864 (II) = 1864*a* using a stellar spectroscope. Speaking of the spectrum he said ". . . . the dark parts are larger than the luminous part, and one might say that these spectra are composed of three bright rays."[1] These are really three bands,

[1] *Astr. Nach.*, 62, 378, 1864.

in the yellow, green and blue, whose heads have the wave lengths $\lambda 5630$, $\lambda 5166$ and $\lambda 4719$ respectively. Huggins and Secchi in 1866 found Tempel's Comet, 1865*f*, had a continuous spectrum, as well as the three bright lines. This was the second to be observed spectroscopically. Again on June 23, 1868, Huggins identified the three bands in the spectrum of Winnecke's Comet, 1868*b*, with those of the Swan spectrum. Also when the spectrum of gases obtained by heating meteorites is observed, the Swan spectrum appears. Huggins pursued the correct method of comparing the comet's spectrum directly with a comparison spectrum. In this way he was able to observe the coincidences to an accuracy of about 6 angstroms, the limiting power of his spectroscope. He added: "The apparent identity of the comet's spectrum with that of carbon, resides not only in the coincidence of the positions of the bands in the spectra, but also in the very remarkable resemblance of the corresponding bands in what concerns their general characters, as well as their relative light. This is well recognized in the middle (green) band where the gradation of intensity is not uniform."

For the next dozen years or more, measures by different men on comets' spectra brought different results as to the wave-lengths of the radiations. This led many to believe in more than one kind of characteristic spectra. In 1879 C. A. Young stated that the differences between results were no more than the limits of the probable errors, and that there was no valid reason for supposing the existence of more than one kind of comet spectrum, slightly modified in different comets by differences in pressure and temperature.

However, from 1864 to 1887, out of 23 comets studied spectroscopically, three had spectra which could not be identified, even approximately. These were 1865*f*, 1867*b*, and 1868*a*. All these showed three bands, displaced from the usual positions found in the spectra of other comets. The observations on the first two were uncertain, but on the last, Brorsen's Comet, they were well studied by Huggins and Secchi. Some dark lines were detected in the spectrum of Coggia's Comet of 1874. In 1881 Tebbutt discovered a comet, 1881 (III). For the first time this was successfully photographed by Janssen, and its spectrum was photographed by Hug-

gins on June 24 and by Henry Draper shortly after. Huggins's photograph showed the spectrum called "cyanogen" and other radiations near λ4050, which he could not identify. Also there was a continuous spectrum, on which were some of the principal Fraunhofer lines. Thus a certain proof was added to that given by Arago, in 1819, by polarization, that solar light is reflected by the rarified materials of comets. Needless to say the photographic plate today gives us spectroscopic data on comets, as on all other heavenly bodies, vastly greater in both amount and accuracy than any visual observations can give. Sodium was also first detected in Comet 1881*b* (1881 (III)), and then in three other comets in the next two years, all of which had small perihelion distances. From displacements of the D lines, the radial velocity of a comet was first detected in 1882, by Thollon and Gouy, and by Lohse and Copeland.

From what has been said we see that the three usual types of spectra are all present—or may be present—in comets. This complicates the explanation. However, the presence of bright lines, or really bands, proves at once that they contain glowing gas, as these bands

could not be merely reflected sunlight. Nor indeed are such bands to be found in the solar spectrum. As for the interpretation of the continuous spectrum, this might of course be due to glowing liquids or solids in the comet. It may *also* be due to reflected sunlight, the Fraunhofer lines being absent merely from relative faintness. We have seen that Fraunhofer lines were indeed present in certain cases.

Eminent authorities took opposite sides during the recent past as to whether a comet was self-luminous or not. At present it seems that a comet is not self-luminous in the true sense; that the only reason it can shine is due to the Sun's radiations falling upon it.

What may be called the typical comet spectrum then consists of a bright continuous spectrum, on which are superimposed several bright bands. If the comet comes extremely near the Sun at perihelion at that time some bright metallic lines appear, for instance those of sodium, magnesium, and iron.

There are strange exceptions, however, Holmes's Comet in 1892 presented a continuous spectrum only. Also Brorsen's Comet in 1868 and Comet 1877 (III) were excep-

tional in not showing the carbon spectrum of bright bands.

Tebbutt's Comet, 1881 (III), showed at first almost a pure continuous spectrum; later cometary bands showed themselves. With the nucleus becoming less bright they became more apparent. On June 29 Fraunhofer lines showed. But on June 24, Huggins, by photography, proved the presence in the ultraviolet of both hydrocarbon bands and solar absorption lines. This proved the essential unity of the whole spectrum. Vogel and Young both traced the carbon bands far down into this comet's tail.

Prof. F. Baldet, formerly of the Observatory of Meudon, France, has made most extensive studies of cometary spectra, and the following discussion is abstracted from his splendid work.[2]

The nucleus presents an emission spectrum, made up of a series of radiations, which are always the same, but not yet identified. The term nucleus is used here, as usual, to mean not only the image of stellar aspect seen in the

[2] *Bul. Soc. Astr. de France*, 39, 577–8, 1925. Also, *Annales de l'Obs. D'Astr. Physique de Paris*, VII, 1926.

midst of the coma, but also the very luminous gas which surrounds this for a few seconds of arc. The nuclei almost always show, with an intensity more or less great, a special spectrum characterized above all by a group of radiations about λ4050, the identification of which is still uncertain. He then concludes:

1. The emission spectra of the nuclei of different comets, at least in all that concerns the most characteristic radiations, belong to only a single type. This statement, based upon the constant ratios of the lines among themselves and upon their variations in general, assumes, however, nothing as to their unity of origin.

2. With the rather feeble dispersions employed, it appeared formed of brilliant lines, and not of the heads of bands as are the spectra of comas and tails.

Out of 115 unidentified radiations, met in course of his study there are only 36 which have not been observed with certainty in several comets.

The brilliant line at λ4313.8 is very fine, and shows no trace of shading. It cannot therefore be identified with the fine head of the band at λ4314.3, characteristic of the

spectra of the hydrocarbons in combustion, and which is always absent in nuclei. This spectrum of brilliant lines is as characteristic of the light emitted by the nucleus as is that of the Swan bands and of cyanogen for the head and as that of the bands of double head of the third negative group of carbon for the tail. The head, i.e., coma and nucleus, has the Swan and cyanogen bands. The tail has an emission spectrum formed by the doublets of the third negative group of carbon and sometimes the negative group of nitrogen. The single exception to this last is the tail of Comet 1910*a*. Even this might be explained by the lack of sufficient dispersion. Also the doublets of the third negative group of carbon are never seen in either nucleus or coma. All three parts of the comet usually have a more or less intense continuous spectrum as a background.

As to the nature of the gases concerned, the spectrum of carbon has not yet been sufficiently studied to give a certain answer. This is because carbonized gas emits different groups of bands according to the process of excitation, and, conversely, different carbonized gases can present the same groups of bands. Whether

different gases therefore exist in different comets can not be affirmed. What is known is that *one* or *several* carbonized gases and sometimes free nitrogen are found and also sodium when the comet is quite near the Sun.

The continuous spectrum has a very variable intensity for different comets. It used to be thought that its explanations lay in the reflection of the solar light from small (hypothetical) solid particles. Recently Fabry has shown the importance of molecular diffusion.

As to the changes of the spectrum with changing distances from the Sun, the following is found. At a distance of 2 or 3 astronomical units the spectrum is almost entirely continuous; the comet simply diffuses the solar light. In proportion to its nearer approach the Swan and cyanogen spectra develop, as well as the peculiar nuclear spectrum. At distance unity, with development of the tail, the third negative group of carbon is seen. Nearer still the spectrum of the nucleus rapidly grows dimmer and that of the tail more brilliant. Next sodium appears, but to the detriment of the Swan spectrum, which grows fainter. The most important element

that complicates this simple succession is the amount of activity in the nucleus, which is very variable from one comet to another. The general conclusion would therefore be that all comets have the same constitution, at least approximately.

S. Orlov states:[3] "That at great distances from the Sun there is no radiation from gaseous material. With decreasing distances the radiations from C_2N_2, CH, CO, and Na appear, only about at 0.1 astronomical unit do Fe and Ni appear."

Baldet[4] gives his theory of the origin of the spectra as follows: "We have seen that when one varies the pressure of the oxide of carbon obtained in the tube with an incandescent cathode, the spectrum of the gas modifies. The most characteristic facts, at very low pressure, are, on the one hand the disappearance of the angstrom bands as well as the considerable enfeebling of the third positive group and of the new spectra which are hardly visible with ordinary exposures; on the other

[3] *Astr. Jahresb.*, 29, 1927.

[4] *Annales de l'Obs. D'Astr. Physique de Paris*, VII, §77, 78, 1926.

hand the increase of light of the first and third negative groups of carbon.

"It seems we can explain as follows: the tungsten cathode, raised to about 2700° absolute, emits a great number of electrons which form a veritable gas in the tube and ionize the molecules. The luminous emission comes at the time from the shock of these electrons animated with a velocity superior to the potential of ionization, against the neutral and ionized molecules and of the shock of the ionized molecules against them and against the neutral molecules.

"These different kinds of shocks must give rise to groups of different bands. At very low pressure, when the shocks of the electrons predominate, the first and third negative group alone are visible. At higher pressure, when the efficacious molecular shocks become more numerous, the spectrum enriches itself with the positive groups already mentioned. The first and third negative groups provide then for the direct shock of the electrons against the molecules of CO.

"The effect of pressure is manifested equally upon the structure of the bands of the third negative group. At very low pressure, the

heads are intense and their shading off rapid—they then resemble bands in the tails of comets. . . . .

"These experimental results bring an important argument in favor of the theory of corpuscular radiation of the Sun given in 1895 by M. H. Deslandres.[5] According to this theory, the Sun projects cathode rays, i.e., electrons, to great distances, which produce the coronal jets and illuminate the gases of comets. We know how well the corpuscular theory, applied to the polar auroras by M. M. Birkeland and Störmer, has given a satisfactory explanation of their peculiarities. But as a more direct verification of an emission of electrons to great distances, we have scarcely noted up to the present any but the appearance of the negative group of nitrogen in Morehouse's Comet.

"So, since the third negative group of carbon obtained at very low pressures, that is to say under conditions which approximate those of the comets where the pressure is much smaller still, is emitted by the direct shock of electrons, and as it presents a complete

[5] *Annales du Bureau des Longitudes*, V, c. 70, 1897.

identity with the spectra of the tails, I have concluded from it that the carbonized and ultra-rarefied gases that they contain are very probably illuminated by the shock of electrons coming from the Sun. (The first negative group must be equally emitted by the tails of comets, but it is unobservable because of the atmospheric absorption in the ultra-violet.) This conclusion appears to me besides to impose upon itself that the spectrum identified is very sensible to the influence of pressure, to the presence of foreign gases, and to different conditions of excitation that profoundly alter it, mingling with it other bands or making them disappear, in other words introducing dissemblances with that of the comets. However, the possibility of a luminescence of the tails by the strongly ionized radiation coming from the Sun, is not at all excluded. . . . ."

Bobrovnikoff,[6] basing his work upon spectra of 22 comets obtained at the Yerkes Observatory with an objective prism, has come to further interesting results. He finds that comets have two distinct types of continuous

[6] *Astroph. Jr.*, 66, 145 and 439, 1927.

spectrum; the first with maximum near $\lambda 4700$ is called "solar type," the second with maximum near $\lambda 4000$ is called "violet type." While variations from the average occur for single comets, it was found that at distance from the Sun greater than 0.7 astronomical unit the violet type predominated, at distances less than 0.7 the solar type. It was found that far from the Sun the CN IV band predominates, but near the Sun the C IV band.

As to jets, both for Halley's Comet and Comet 1913 (V), their spectrum was found to be due mostly to cyanogen. These jets apparently differ from the regular emissions forming the head of the comet only in the velocity of ejection, as was shown by a comparison with the spectra of the envelopes. These latter give principally the cyanogen and Swan spectrum. The ordinary cyanogen bands never extend far into the tail.

Bobrovnikoff[7] considers the origin of cometary spectra under three possible heads: (a) thermal action of the Sun; (b) solar corpuscular emission; (c) direct influence of the Sun's rays

[7] *Astroph. Jr.*, 66, 439, 1927

producing fluorescent phenomena. After rejecting the first two and accepting the last explanation as most probably the true one he adds: "All difficulties of the corpuscular theory vanish in the case of fluorescence." And again; "If the theory of fluorescence be true, comets in the last analysis depend for their luminosity on the Sun and are intrinsically dark bodies."

Zanstra,[8] who has done most important work on this subject, discards the theory of electric discharges. He concludes that the bright line and band spectra of comets are caused by sunlight, which theory satisfactorily accounts for the observed brightness of the head. He considers the mechanism as nearly always that of resonance, but one case of fluorescence is known—for 5 iron lines in the Great Comet of 1882.

[8] *Observatory*, 52, 9, 1929.

CHAPTER VII

Halley's Comet

"And. . . . saw the angel of the Lord stand between the earth and the heaven, having a drawn sword in his hand stretched out over Jerusalem."

Of all comets there is no possible doubt but that Halley's Comet has had the most important influence on astronomy. This comes not only from the fact that its periodicity was established before that of any other, as briefly mentioned in Chapter I, but also because its history can be traced accurately for over two thousand years. Its well-timed appearances at or near several important events in history has also given it an added interest not only to the superstitious, but also to the student of human conduct and reactions.

Edmund Halley, who most justly is immortalized by having his name appended to this famous comet, was born in England in 1656. He showed great ability in mathematical studies at Queens College, Oxford, and when but twenty published a paper on planets' orbits which placed him high among theoretical astronomers.

A few years after the coming of the Great Comet of 1680, Newton published his *Principia*, incidentally urged on thereto by Halley, who also furnished the necessary funds. In this work Newton explained the theory of gravitation and applied it to the orbit of the above-mentioned comet. He set up a method of geometrical construction by which the visible part of a comet's path could be represented, and a parabolic orbit calculated. He considered it probable that some comets moved really in elongated ellipses, which could not be differentiated from parabolas in the small arc visible to observation. Halley concurred in the latter opinion.

Halley seriously undertook to calculate the orbits of twenty-four comets which had enough observations for his purposes. The catalogue of their elements was published in 1705. Table 7 shows his elements, of three of which we shall speak.

Halley wrote as follows: "Now, many things lead me to believe that the comet of the year 1531, observed by Apian, is the same as that which, in the year 1607, was described by Kepler and Longomontanus, and which I saw and observed myself, at its return, in

1682. All the elements agree, except that there is an inequality in the times of revolution; but this is not so great that it cannot be attributed to physical causes. For example, the motion of Saturn is so disturbed by the other planets, and especially by Jupiter, that his periodic time is uncertain, to the extent of several days. How much more liable to such

TABLE 7

Elements of Halley's Comet

	COMET 1531	COMET 1607	COMET 1682
Ω	49° 25′	50° 21′	56° 16′
i	17° 56′	17° 2′	17° 56′
π	301° 39′	302° 16′	302° 53′
q	0.56700	0.58680	0.58328
	Retrograde	R	R

perturbation is a comet which recedes to a distance nearly four times greater than Saturn, and a slight increase in whose velocity would change its orbit from an ellipse to a parabola? The identity of these comets is confirmed by the fact that in the summer of the year 1456 a comet was seen, which passed in a retrograde direction between the earth and the sun, in nearly the same manner; and although it was not observed astronomically,

yet, from its period and path, I infer that it was the same comet as that of the years 1531, 1607 and 1682. I may, therefore, with confidence, predict its return in the year 1758. If this prediction is fulfilled, there is no reason to doubt that the other comets will return."

As Halley died in 1742, at the age of eighty-five, he of course did not live to see how his prediction came out, nor could he have expected to.

As the year 1758 drew near, the attention of astronomers was turned to Halley's prediction. It is a curious fact that Frenchmen rather than Englishmen undertook seriously to compute what had happened to the comet on its long journey out and back, and when its time of perihelion would be. While Halley had been able to see and indeed estimate roughly the effects of Jupiter and Saturn (Uranus and Neptune being then unknown) yet the theory of perturbations was not advanced enough for him to come to definitive results. Incidentally the intervals between the 1531, 1607, and 1682 returns had been 27,811 and 27,352 days, showing that successive periods differed by 459 days.

So Clairaut, a French astronomer, under-

took the laborious calculations—laborious indeed for there were no computing machines in those days, and few convenient tables for calculation! He was assisted by Lalande and Madame Hortense Lepaute, and they just managed to get the first report ready for the Academy of Science in November, 1758.

Clairaut says: "The comet which has been expected for more than a year has become the subject of much curiosity. . . . .True lovers of science desire its return because it would afford striking confirmation of a system in favor of which nearly all phenomena furnish conclusive evidence. Those, on the contrary, who would like to see the philosophers embarrassed and at fault hope that it will not return and that the discoveries of Newton and his partisans may prove to be on a level with the hypotheses which are purely the result of imagination. Several people of this class are already triumphing, and consider the delay of a year, which is due entirely to announcements destitute of all foundation, sufficient reason for condemning the Newtonians. I here undertake to show that this delay, far from invalidating the system of universal gravitation, is a necessary consequence aris-

Halley's Comet, May, 1910
Photographed by H. D. Curtis at Lick Observatory

Halley's Comet, May, 1910
Photographed by H. D. Curtis at Lick Observatory

ing from it; that it will continue yet longer, and I endeavor to assign its limit."

Clairaut indeed assigned a delay of 618 days, 518 due to Jupiter, 100 due to Saturn. This placed the date of perihelion passage in April. Due, however, to neglected terms in the equations and unknown bodies, he said the date might be out by one month. It was discovered on Christmas night, 1758, by an amateur astronomer, Palitzsch, near Dresden. It was seen in France on January 21 by Messier who observed it for three weeks. Messier was Delisle's assistant, the latter being director of the Observatory of Paris. Delisle from some contemptible motive[1] refused to allow Messier to announce his observations, and the comet was lost in the twilight as it neared perihelion. Delisle—and the innocent Messier—were both punished as it was with great difficulty that the French Academy were convinced that the observations were not forgeries, when once the stupid director brought them forth.

The comet passed perihelion on March 12, 1759, or within thirty-two days of the pre-

[1] Chambers, *The Story of the Comets*, 117, 1910.

dicted date. The delay had been only 586 instead of 618 days. The work of the three French astronomers, which meant six months of the most intense labor to calculate the perturbations by the methods then in use, justly ranks them next to Halley himself. After perihelion passage, the comet was seen throughout April and May but best in the Southern Hemisphere.

The importance of this return of Halley's Comet cannot well be overestimated. It proved that some comets at least are definite members of the Solar System, and that Newton's laws fitted their motions as well as those of the planets. Also Halley's prediction was triumphantly vindicated.

The next return was due in 1835. Meantime theoretical astronomy had made great advances, and Uranus had been discovered, adding another body whose perturbing force had to be reckoned with. In 1820, Baron Damoiseau of Paris gained the prize offered by the Academy of Sciences of Turin for the best paper on the perturbations of the comet since 1759. He set November 4, 1835, as the date of perihelion passage. Comte de Pontécoulant, following similar lines, predicted

November 12, 1835. Both neglected the influences of some of the smaller planets. Later a German, Rosenberger of Halle, with the thoroughness characteristic of his countrymen, decided to investigate the comet's orbit all the way back to 1682, allowing not only for the major planets, but also Mars, Earth, and Venus. He added some allowance for the hypothetical "resisting medium" then thought to affect Encke's Comet, by Encke himself. He came to two results: without "resisting medium" effects, November 11, 1835; with such effects November 3, 1835. Another German, Lehmann, feeling that there was still room for improvement, worked back to the 1607 return. He decided on November 26 as the date of perihelion passage. The average of November 4, 12, 11 and 26 is November 13; the actual date was November 16, 1835, which meant 28,006 days had elapsed since the 1759 perihelion.

Calculations for the next return, which were promptly taken up, showed that Jupiter would shorten the period of the comet about 800 days. Pontécoulant indeed calculated the perturbations and the perihelion passage for 1910, and published his results as early as

1865.[2] In this the date of perihelion was determined as May 24.37. However, as the time for the return drew near, Cowell and Crommelin in England, examining into Pontécoulant's published results, found some impossible figures. This and the importance of the problem induced them to undertake a complete recomputation. This was done in such a thorough manner that it will long remain a model for similar cases. They deduced April 8 as the date of perihelion, a month from that deduced by Pontécoulant. The actual date was April 19, 1910.

However, they pushed their researches in another direction, which was to determine the perturbations for past centuries, and thus determine which of the comets of antiquity were certainly returns of Halley's Comet. Hind[3] had long before made many identifications; also Langier,[4] Pingré and Burckhardt should be mentioned in this same connection. The dates of return, so far identified, were in B.C. 240, 87, 11; A.D. 66, 141, 218, 295, 373, 451, 530, 607–8, 684, 760, 837, 912, 989, 1066,

[2] *Comptes Rendus*, 58, 826 and 915.

[3] *The Story of the Comets*, p. 50 et seq.

[4] *Comptes Rendus*, 23, 183, 1846.

1145, 1223, 1301, 1378, 1456, 1531, 1607, 1682, 1759, 1835 and 1910. Crommelin states that a comet seen in 467 B.C. was not improbably Halley's Comet, but the data are insufficient to be certain about it. It will be noticed that the only missing date after 240 B.C. is about 163 B.C. For the earlier returns we are indebted mostly to the Chinese for the observations, for the later ones to Europeans. As we have briefly sketched the history of the comet from the standpoint of its orbit, we will now take up these various returns from the historical and descriptive side.

Chinese records give a comet appearing in 240 B.C., which according to the work of Cowell and Crommelin was Halley's Comet. No identification is possible for 163 B.C., though comets were seen in 166 and 165 B.C. In the *Theatrum Cometicum* of Lubienietz there is mention of a bright comet in 87 B.C. The Chinese recorded a comet visible in August, and modern calculations put the perihelion passage of Halley's Comet during that month. There seems no doubt of the identification. In 11 B.C., the Chinese made observations for nine weeks on a comet, from which a rough orbit was calculated by Hind.

The elements of this orbit are sufficiently near to those of Halley's Comet to leave practically no doubt of its identity. Recent work has confirmed Hind's conclusions. The comet of 66 A.D., mentioned elsewhere (p. 11) was seen by the Chinese for seven weeks. Hind again calculated a rough orbit and concluded this was Halley's Comet. It was this appearance that started the career of the comet as a prophet of terrible calamities, for Josephus considered it a forewarning of the destruction of Jerusalem and so large a part of the Jewish nation.

The 141 A.D. comet, which was seen for four weeks in China, and also that in 218 which was visible for six weeks, were certainly Halley's Comet. The identification with the comet of 295, visible seven weeks, and seems less certain though very probable. More recently Hirayama,[5] using Chinese observations, has proved that a comet which passed perihelion on Feb. 13, 374, was certainly Halley's Comet. The comet of 451, visible for thirteen weeks in China, was evidently a striking object. Its orbit, calculated by

[5] *Observatory*, 34, 193–9

Langier, proved it to have been Halley's Comet. It appeared indeed at one of the terrible crises of the world's history, for this was the date of the Battle of Chalons. In this battle the Huns under their king, Attila, were finally defeated by the allied Christian armies under the Roman general Aetius. Bad as were the Middle Ages, had the Huns conquered, civilization would indeed have been put back for centuries at least.

A great comet appeared in 530 or 531, of which it is recorded that it was very large and fearful, being seen in the west for three weeks. Its rays extended to the zenith. Hind identifies this as Halley's Comet. A comet observed in China in 607 is thus identified by Cowell and Crommelin. But the Chinese records are here most confusing. Hind thought the comet of 608 to be the proper one; in any case we may be sure one or the other of the comets of the years 607–8 was Halley's Comet. Comets in 684, 760, and 837 proved to be returns of Halley's Comet. The comet was visible five and eight weeks respectively for the first two. The Chinese record four comets for 837, so that year must have been a remarkable one for such bodies. The first

of these was Halley's. The identity of Halley's Comet in 912 caused trouble. Hind's result for perihelion passage differs four months from that of Cowell and Crommelin. The latter stated that the computed position could not be certainly identified with that of any comet recorded in that year. But a recently discovered Japanese manuscript gives observations which make the identification satisfactory.

In 989 the Chinese recorded observations of a comet visible for five weeks. Burckhardt calculated its elements, which proved its identity. This comet is mentioned also by Anglo-Saxon writers. The return of the comet in 1066 was noteworthy because in that year the Normans under William the Conqueror invaded England. Also because we have the oldest contemporary picture of the comet which is embroidered in the famous Bayeux Tapestry, said to have been the work of Queen Matilda, William's wife. Zonares, a Greek historian, said it was "large as the full Moon, at first without a tail on the appearance of which it diminished in size." The Chinese say that it was visible for sixty-seven days after which "the star, the vapor and the

comet all disappeared." There seems no doubt that the comet was a brilliant and striking object, judging by the large amount of attention it received.

The 1145 return, which took place in April and May, was not so striking. In August and September, 1222, it was recorded in England as a star of the first magnitude, with a tail. In 1301 the comet was a brilliant object, visible for six weeks, and observed in both China and Europe. In 1378, though extensively observed, it seems to have been less striking. In 1456 the Chinese described it as having a 60° tail, with a head that was at one time round and the size of a bull's eye, the tail being like a peacock's. It was visible for a month, perihelion passage taking place on June 8. Halley thought this was a return of the comet, when he was investigating the subject, and Hind later proved it.

As Constantinople had been captured by the Turks in 1453, they then appeared in grave danger of overrunning and conquering all Europe, so that the appearance of Halley's Comet caused the greatest terror. The statement that the pope, Calixtus III, issued a bull excommunicating the comet has been proved

false, though it has found its way into many books. The story appears to have had its origin in a paragraph of Platina, in his *Vitae Pontificum*, 1479. He was then in Rome and archivist of the Vatican. He wrote:[6] "A hairy and fiery comet having then made its appearance for several days, as the mathematicians declared that there would follow a grievous pestilence, dearth and some great calamity, Calixtus—to avert the wrath of God—ordered supplications, that if evils were impending for the human race, he would turn all upon the Turks, the enemies of the Christian name. He likewise ordered, to move God by continual entreaty, that notice should be given by the bells to all the faithful, at midday, to aid by their prayers those engaged in battle with the Turk."

Nevertheless, though no bull was issued, the pope evidently thought it prudent to invoke the Deity against the probable ills to follow the comet's appearance. Nor is he to be blamed for having the same scientific beliefs as other educated men of his times.

The comet on its return in 1531 was visible

[6] *Pop. Astr.*, 16, 482, 1908.

for five weeks, and in 1607 for nine weeks. Its next return in 1682 was observed by Halley himself. It was during this apparition that bright jets, associated with the nucleus, were seen by Hevelius.

On the return of Halley's Comet in 1835, it was not discovered until August 6, though search had been made for many months previously. Dumouchel, in Rome, was the discoverer, and the comet was found near its computed position. It was so faint that it was not seen elsewhere until August 21, when Struve saw it at Dorpat. His observations showed that Rosenberger's ephemeris was wrong by only 7′ in right ascension, and 17′ in declination. The comet meantime was rapidly becoming brighter so that on September 23 Struve saw it with the naked eye. Bessel on October 22 drew the head of the comet with wings attached to the nucleus, quite like those photographed on May 27, 1910. For the next month a tail, estimated by various European observers at from 20° to 30° long, was seen. Perihelion passage occurred on November 15.

Maclear, at the Cape of Good Hope, did not record any observations until January 24,

1836. Whether this was because he did not see the comet earlier—which scarcely seems possible—or whether he was occupied with other duties, is not now apparent. On January 24, he described it as being of the 2.3 or 3 magnitude, with no tail. For the next week he described some surprising phenomena, as indeed had been already done by observers in Europe during the previous fall. We quote his final statement: "Throughout the succeeding three months the coma went on increasing, until the outline finally became so faint as to be lost in the surrounding darkness, leaving a blind nebulous blotch with a bright center enveloping the nucleus of variable brightness, depending on moonlight, or the state of the atmosphere, and variable distance." The comet was followed until May, 1836.

On its last return Halley's Comet was discovered by Wolf at Heidelberg, on September 11, 1909, when over 300,000,000 miles from the Sun and even farther from the Earth. It was photographed the next night at Lick Observatory, California, by H. D. Curtis, for whom the writer was then acting as assistant. Later a search at other places showed that it was on a Helwan, Egypt, plate of August 24.

It was followed, photographically, until June 1911, when it was 520,000,000 miles from the Sun.

This return being so recent, and the comet being considered such an important object, the number of photographs taken at many leading observatories was immense. Also very numerous visual observations were made, and many spectrograms obtained. In fact, the data are so numerous that it is impossible to discuss them in detail. Only certain points of interest can be touched upon here. The writer will add some personal impressions, for due to the wonderful climate of Mount Hamilton, it is doubtful if anyone besides Dr. Curtis actually saw Halley's Comet oftener than himself, up to the time it ceased to be a naked-eye object in the summer of 1910. As the writer is familiar with the hundreds of photographs taken at the Lick Observatory, much of what is to be said will be based upon these.

After September 12, when the comet appeared as a faint nebulous speck on the plate, the image indicating a diameter of 13,000 miles only, it rapidly increased in size. Table 8, due to Curtis,[7] gives in condensed form the

[7] *Pub. A. S. P.*, 22, 117–130, 1910.

TABLE 8
DIMENSIONS OF HALLEY'S COMET

DATE	COMA	NUCLEUS	TAIL	TAIL*
1909				
September 12	13,000m	6,000m		
September 13		5,000		
September 22		2,900		
November 14		2,400		
December 13		5,600		
December 14	220,000			
December 16			430,000m	
1910				
January 7	79,000	2,600		
January 28	181,000		4,700,000	
February 4	141,000	5,500	8,800,000	
February 11	170,000			
February 28	153,000			
March 3		4,000		
April 12		6,400		
April 19	129,000			
April 21			9,200,000	
April 23		2,300		
April 28	118,000			
April 30			19,000,000	
May 1	122,000	1,400		
May 5	161,000	800	27,800,000	31°
May 9		1,000		30°
May 10			24,400,000	
May 17			18,900,000	
May 19			18,600,000 vis	
May 20		400		
May 22		300		
May 23	194,000	290	16,000,000	
May 28			17,600,000	32°

TABLE 8—*Concluded*

DATE	COMA	NUCLEUS	TAIL	TAIL*
1910				
May 31	315,000			
June 1		1,000		15°
June 2	308,000		21,000,000	
June 8	340,000			
June 11		2,300		
July 1			18,000,000	
1911				
April	30,000			

* As photographed by Ellerman in Hawaii.

diameter of the head, i.e., coma, of the nucleus, and the length of the tail. The contractions of the coma, near perihelion, which is a usual and well-known pheomenon, is excellently shown.

It must be understood that both atmospheric conditions and lengths of exposure, as well as type of telescope employed, keep the figures for coma and nucleus from being strictly comparable. For instance, the nucleus would in general be larger when the comet was faint, from relative over-exposure. During December, Aitken made a visual measure of the halo about the head showing it to be 15′ or 550,000 miles in diameter.

Due to relative position and lag in activity, the comet was rather a poor object until after its perihelion passage which took place on April 19. From then on until summer it was brilliant, and showed many interesting changes and phenomena. The inner coma varied greatly from night to night. Small, sharp jets, sometimes showing a spiral effect, were frequent. Bright, strong appendages and wings, generally asymmetrical, frequently appeared at times of greatest brightness. For instance, on May 14, both head and envelopes were markedly asymmetrical, being stronger on the south side. From the elongated nucleus proceeded two remarkable wings, nearly as bright as the nucleus itself. One was in the tail's axis and 50″ long, the other at an angle of 59° was 70″ long.

An almost explosive change is thus described by Curtis:[8] "Both plates were taken on May 23, one hour and fifty-nine minutes apart. On the former plates the nucleus is sharp at the rear, and strong jets proceed from it on the side toward the Sun at an angle of 60° with the axis of the tail. The jets give a

[8] *Pub. A. S. P.*, 22, 121, 1910.

spiral effect to the head and are so bright at the nucleus that this appears wedge-shaped. In the next very bright growths, roughly spherical, have formed on each side of the nucleus, with a slightly fainter patch at the rear which joins the two globes of matter. From edge to edge the new growth measures 37″ = 3570 miles. The photographic diameter of the brightest part of the nucleus on the first plate is 3″ = 290 miles; this may well be considerably larger than the true nucleus. A plate exposed from 8:31 to 8:49 P.S.T. shows the nucleus as still sharp and with no trace of the appendages. On the next plate exposed from 8:55 to 9:55 P.S.T., the head is so bright as to mask considerably any details about the nucleus, which appears less sharp and roughly spherical, with an estimated diameter of 12″ = 1160 miles. At 10:15 the nucleus is sharp; small faint traces of the outer parts of the new growth can be seen, apparently detached from the nucleus. These globular appendages seem then to have reached their full growth in the interval of about 50 minutes, though the interval may be considerably shorter. Under this assumption the lower limit of the velocity

of movement outward within 20″ of the nucleus was 0.88 km. per second, and it may have been considerably higher. It would have been of interest to trace this growth further. May 24 was cloudy."

Bobrovnikoff,[9] using plates available later from other stations, has followed the question further as follows:

May 23,	$20^h:00^m$,	Many jets around nucleus.
May 24,	3 :13,	Nucleus rather large. Spectrum unusual, steady bright jet.
	3 :42,	Nucleus still larger. Violet part of spectrum weak.
	4 :10,	Nucleus very much larger. Appendages. Extinction of violet part of spectrum. Faint halo.
	6 :18,	Two globular growths on each side of nucleus.
May 25	,	Double nucleus and two systems of envelopes. Halo brighter.
May 26	,	Nucleus double. Halo much brighter.

In his opinion these striking transformations may be described as an explosion of the nucleus. The spectrum of the jets was found to be gaseous with a preponderance of cyanogen.

[9] *Astroph. Jr.*, 66, 145–169, 1927.

Halley's Comet was due to pass across the Sun's disc on May 18, but during the night for Europe and America. An expedition therefore was sent to Hawaii for the special purpose of observing this. Ellerman, observing with a 6-inch telescope, was able during the critical interval to see small sun-spots most clearly but absolutely no trace of the comet's nucleus could be detected. Had the latter been a single, solid mass as much as 200 miles in diameter, it should have been seen without difficulty.

The Earth was due to pass through the comet's tail on May 19, so a careful lookout was kept for any possible meteorological effects which could have been caused thereby. W. J. Humphreys[10] of the United States Weather Bureau sums his investigations, based on reports from the whole world, as follows: "The halos, coronas and other phenomena listed above were both widely scattered and, in some respects, distinctly unusual; and their occurrence coincident, as near as can be determined, with the passage of the earth through the tail of the comet suggests

[10] *Pub. Am. Astron. Soc.*, 2, 17, 1915.

for them a cosmical origin. Still they were far from universal, and besides they have all been seen before when there was no comet to which they could be attributed; and, therefore, while admitting the possibility, in this case, of a cometary influence, it would seem rash, without additional evidence, to conclude that the comet was the principal or even partial cause of any of the appearances mentioned."

It may be added that, while no trace of the effects of entering the tail could be detected on any of the critical nights, still from its relative position on former and later dates it was concluded that the Earth did not pass centrally through the tail, but only through its outer edges. Brilliant moonlight, however, was enough to wholly mask any faint glows or other similar appearances in the night skies at the date.

The tail was a very fine object in the morning sky up to the date of our passage through it. At Mount Hamilton the following estimates were made by Curtis,[11] the times being (old) G.M.T.: May 19.0, two branches,

[11] *Pub. A. S. P.*, 22, 128, 1910.

northern one stronger. Total width 17°. May 20.0, tail much fainter than the previous morning, 12° broad in Pegasus. May 20.7, perhaps 20° of tail visible in west in strong twilight and moonlight. May 21.0, no trace of tail in east. May 21.7, 20° to 30° of tail in west. He last saw the comet with the naked

TABLE 9

BARNARD'S DERIVATIONS FROM RESULTS OF OBSERVATIONS OF HALLEY'S COMET

STATIONS	INTERVAL	HOURLY MOTION	RECESSION PER SECOND	
			From Comet	From Sun
	h	′	*km.*	*km.*
Yerkes-Honolulu..............	4.25	3.60	37.2	63.9
Yerkes-Beirut......	15.15	5.17	53.3	80.0
Honolulu-Beirut.............	10.90	5.78	59.7	86.4

eye on June 28, when its effective brightness was 6 magnitude. On May 18, Barnard at Yerkes observed the tail as 107° long; the writer and others at Mount Hamilton were able to trace it to a length of about 130° to 140°. In early May the comet's head was magnitude 2.

On June 6, 1910, a broken part of the tail could be traced as it receded from the head.

Barnard[12] on the basis of plates taken at Yerkes, Honolulu, and Beirut derived the results shown in table 9.

On the comet's return trip from the Sun, Innes was able to measure the comet to August 12, and Perrine to August 26. On this latter date its total light equalled a star of magnitude 9. By December it had decreased to magnitude 12.[13] On January 8, 1911, Barnard found that it had a diameter of 33″, that it was round, slightly condensed, and had no nucleus. The magnitude was 13 to 14. On February 25, at Algiers, it was found to be of magnitude 14. Barnard in April found its diameter to be 10″ and its magnitude 15. On May 27, Curtis at Lick photographed it as of magnitude 16, when it was barely visible on the plate.

A series of measures of its brightness,[14] during its whole apparition, was made at Helwan, Egypt. There the visual magnitude was consistently found to be one magnitude brighter than the photographic. It was last seen on April 29, 1911, but last photographed

[12] *Pub. Am. Astr. Soc.*, 2, 38, 1915.
[13] *Observatory*, 34, 56, 1911.
[14] *Jr. B. A. A.*, 22, 204, 1912.

on May 18. Its photographic magnitude 238 days before perihelion passage was the same as that 394 days after showing the lag in excitation, which is discussed in general elsewhere (p. 28). Table 10 gives the Helwan photographic magnitudes.

TABLE 10

HELWAN, EGYPT, PHOTOGRAPHIC MAGNITUDES

DATE	MAGNITUDE	DATE	MAGNITUDE
1909		*1911*	
August	15¾	January	15¼
September	15	February 5	15½
October	14¼	March (first half)	14½
1910		March (second half)	15¼
November	14¼	April	15½
December	15	May	15¾

Of the many important studies made on Halley's Comet, a few will now be touched upon. Orloff[15] worked out the mass of the nucleus of the comet, basing his results on the period May 24 to July 4, 1910, during which he could detect phase effects. These latter proved that the nucleus shone almost wholly by reflected light; the intrinsic light being

[15] *Bul. St. Petersburg Acad.*, No. 5, 1913; and *Pub. A. S. P.*, 25, 175, 1913.

negligible. His conclusions were based on two suppositions: (1) that the nucleus was one solid body, (2) that it consisted of solid particles 2 mm. in diameter. No smaller particles could be assumed, for then radiation pressure would have produced observable perturbations. Taking the mass of the Earth as 1, he then found that $\frac{1}{6 \times 10^5} >$ mass of nucleus $> \frac{1}{2 \times 10^{14}}$. From this he concluded that the minimum mass of the nucleus was 30×10^6 tons. He proved that in such studies the phase effect could not be neglected.

As for the mass of the tail, some results[16] by Schwarzschild and Kron are given. "The reasonable assumption is made that the particles in the comet's tail are fluorescent molecules; from many accordant physical investigations it is shown that the size of such molecules for the average hydrocarbon gases is of the order of $\frac{1}{10^6}$ mm. From this it would follow that the mass flowing along the cross section of the tail per second would be only

[16] *Astroph. Jr.*, 34, 342, 1911; *Pub. A. S. P.*, 24, 138, 1912.

about 150 grams (5 oz.), while the density, in terms of the density of air, is infinitesimally small, only $\frac{1}{4 \times 10^{24}}$. . . . . If the Earth were exposed for an entire day to a tail of such density with a velocity of 60 miles sec, the total mass caught by the Earth in its passage would be a matter of only a few hundred tons.

Such a result bears out most forcibly what has been already said about the extremely low density that must be assigned to the tail of a comet.

Baldet found that the head gave radiations characteristic of comets—the spectrum of cyanogen and the Swan spectrum, with an intensity sufficient so that one could affirm that they did not extend into the tail. This point was confirmed by plates of other observers. A plate on May 5 showed traces of the red spectrum of cyanogen. The comet showed a continuous spectrum sufficiently marked.

To other observers the spectrum of the tail showed oxide of carbon at very low pressure. It resembled in all points that of Comet Morehouse. Sodium rays were registered at the

Lowell Observatory[17] when the comet was 0.69 unit from the Sun. Also the relatively intense continuous spectrum showed a great number of Fraunhofer lines.

However, this comet offered a chance to study variations in spectra, due to its brightness and long period of visibility. Thus W. H. Wright, on October 22, 1909, obtained a purely continuous spectrum from λ3750 to λ5000. This was six months before perihelion passage. Deslandres and A. Bernard saw the first bands of cyanogen appear. Last of all, near the Sun, the sodium D lines appeared.

Halley's Comet[18] according to a study by Bobrovnikoff showed distinctly two types of continuous spectrum, which may be denominated the solar, with maximum about λ4700, and the violet, with maximum about λ4000. The change took place about 1.2 astronomical units from the Sun, the violet being characteristic beyond this limit, the solar within it. His work was based upon three monochromatic images at λ3883 (CN IV), λ4020–4100 (C H) and λ4737 (C IV). All images reached

[17] *Lowell Obs. Bul.*, 2 and 3, 1911.
[18] *Astroph. Jr.*, 66, 145, 1927.

their minimum size about a month after perihelion passage.

He adds: "The reflected solar spectrum makes its first unmistakable appearance at about the middle of February. At the end of this month the solar spectrum is already stronger than the violet and in April and May it is the predominant feature of the whole spectrum. On May 29 the first signs of the violet spectrum reappear and on June 11 the maximum of intensity of the continuous spectrum is in the violet, resembling thus the conditions on February 3. This is in contradiction of the general but unwarranted opinion that when comets are far from the sun they shine chiefly by the reflected sunlight."

Halley's Comet did not come nearer than about 5 million miles of the Earth's orbit, but despite this fact there is a most interesting meteor stream connected therewith. These meteors are known as the Eta Aquarids, and are seen during about two weeks including the last day or two of April and early May. These meteors were seen as early as 1870[19] and recognized as a real stream, and various guesses and partial proofs were made that

[19] *Meteors*, Chapter VIII.

they were connected with Halley's Comet. It was not until 1909 that the writer made the necessary observations and calculations to make the proof complete. He also first proved the daily motion of the radiant. Among other interesting facts brought out was that meteors at least 11 million miles out from the comet's orbit were still moving approximately parallel thereto and were evidently part of the system. Altogether it furnished another excellent example of the connection between comets and certain meteor streams. This proof was soon followed by similar work by Hoffmeister.[20]

Since then various members of the American Meteor Society have often observed this stream, fully confirming the motion. This has just been most successfully done in 1929 by R. A. McIntosh[21] of New Zealand. His work proves the stream still to be most active though the comet passed perihelion nineteen years ago. From the United States, these meteors are seen shortly before dawn in the southeast. They usually move relatively slowly, are fairly bright, and often leave persistent trains.

[20] *Astr. Nach.*, 191, 251, 1912 and 196, 309, 1913.
[21] *Pop. Astr.*, 37, 528–34, 1929.

CHAPTER VIII

Biela's Comet

"Thereby hangs a tale"—Shakespeare

Von Biela, an Austrian officer, after whom the comet now under consideration was named, was not its first but its third discoverer. However, circumstances, about to be mentioned briefly, had prevented any special attention from being paid to this rather insignificant comet at its two previous appearances.

A Frenchman, Montaigne at Limoges, discovered a comet on March 8, 1772, which he observed until March 20. Having no suitable instruments, his observations were very approximate. Messier, however, saw it four more times up to April 3. It was thus observed barely four weeks at this apparition.

Pons, on November 10, 1805, and Bouvard, on November 16, discovered a comet, whose coma in two weeks grew to 6′ in diameter. It approached the Earth most nearly on December 8, when Olbers was able to see it with the naked eye. Schröter observed it this same night, finding the comet 30,000 miles in diameter as seen with naked eye, but only

6000 as seen in his telescope. He measured the central condensation as 112 miles in diameter, the actual nucleus as 70 miles. It was seen this time for four weeks also. Although elliptical elements were calculated by several persons, and the identity with the former comet of 1772 was suspected, for some reason no one ventured on the comparatively simple prediction as to when it would return.

Hence, when Von Biela at Josephstadt, Bohemia, discovered a faint comet on February 27, 1826, neither he nor anyone else suspected at first this was a return of a comet which had already been observed twice in the last half century. This time the comet remained visible for eight weeks, and an elliptical orbit of moderate eccentricity was found to satisfy the observations. It was now recognized that the comet was the same as the two mentioned above, but its third discoverer had the luck to have his name permanently attached. In table 11 the three orbits are given along with that for the 1852 return, to show the changes that occur between returns.

It being established that the comet was one of short period and that it would evidently return in 1832, investigations were under-

taken by Damoiseau, Olbers and Santini. The latter fixed the date of the next perihelion at November 27, 1832. It returned within twelve hours of the exact prediction. Olbers also called attention to the fact that the comet would almost cut the Earth's orbit. This fact, taken up by the papers, was the

TABLE 11

ORBITS OF BIELA'S COMET

	PERIHELION PASSAGE			
	February 16, 1772	January 1, 1806	April 21, 1826	September 23, 1852
Perihelion distance....	0.9860	0.9070	0.9024	0.8606
Eccentricity..........	0.90314	0.74571	0.74660	0.75586
Inclination	17° 08′	13° 37′	13° 34′	12° 33′
Node..................	257° 16′	251° 16′	251° 27′	245° 51′
Longitude of perihelion..............	110° 09′	109° 38′	109° 49′	109° 8′

basis for a great "comet scare." Actually the comet would come to the critical point on the orbit about a month before the Earth would reach it, but this little circumstance was either not understood by or ignored by the sensational writers of the day. So the Earth was still about 50 million miles away when the comet swept by, and of course no harm could

result. The comet was visible in all eighteen weeks during this return.

Due to the relative positions of Sun, Earth, and comet when the latter returned to perihelion in 1839 it was always in the twilight zone, when near enough to be visible, and hence was not discovered. This perihelion passage was calculated to have taken place on July 13, 1839.

February 11, 1846 was calculated by Santini as the date for the next perihelion. He had already done other noteworthy work on this comet's orbit. It was also known that the comet would be in a most favorable position for observation, so its return was expected with eagerness. This was due to the desire for obtaining observations for checking the theory of its motion, but no one had any idea of the surprises in store for the scientific world that this 1846 return was going to furnish.

At its 1845–46 return Biela's Comet was first seen by Di Vico at Rome on November 26. It was seen at Berlin by Encke on November 28, but was extremely faint. It was seen at Cambridge, England, on December 1 and 3, and at several other places in Europe during the month. The most remarkable

circumstance attending this return of the comet was that it was attended by a companion, which was first detected at Yale on December 29. When discovered this companion was merely a faint nebulous spot, barely distinguishable; but from that time it increased in brightness faster than Biela. On January 13, when it was independently discovered at Washington, it was estimated as one-fourth the intensity of Biela. Its further changes will be shown in the quotations from the actual observers. The companion was constantly growing more distant from the original comet, being about 1′ on January 1, $2\frac{1}{2}'$ on January 23, and nearly 3′ on February 13.

At Yale the duplication was detected by Bradley and Herrick on December 29, with the 5-inch refractor. The position angle of one to the other was estimated by each observer drawing diagrams of what he saw. The Moon was absent and the sky favorable. On the nights of March 30 and 31, the same observers estimated the distance to be 16′, but the companion was barely visible. Bradley was able to measure it as late as April 16.

The following is quoted from the *American*

Journal of Science, II, 1, 293, 1846: "During its present return, it has exhibited a very remarkable appearance. When first observed through the 5-inch refractor at Yale College, December 29, 1845, the comet was attended by a faint nebulous spot preceding, estimated to be rather more than a minute of space from its brightest point. The few subsequent observations which the clouds and moonlight permitted here [i.e., Yale], before the middle of January, showed this secondary comet to be brighter than the principal, and slowly departing from it. This surprising phenomenon was first publicly announced in this country by Lieutenant Maury, of the Washington Observatory." Where these observations were published more fully, if they ever were, is not known to the writer. Further, under modern conditions, priority of announcement is always counted as priority of discovery, unless the case is most unusual. It seems that the importance of the Yale observations were hardly appreciated by those who made them.

In England, Professor Challis at Cambridge on January 15, first saw two comets and then changed his mind and thought he was wrong.

On January 23 he again saw two, but even yet was troubled with many misgivings, having it evidently in his head that no well-behaved comet ought to divide in two. On January 24 he again saw both and apparently was finally convinced that his eyes did not deceive him. He then published his observations. He said that the reason he did not spend more time confirming matters on January 15 was that he was anxious to get at the work on the search for the new planet, i.e., Neptune. On the whole, 1846 seems to have been a year of hard luck for the professor. He and Airy share the serious blame for losing to England the undisputed priority in the discovery of Neptune, and here he lost another opportunity for making a unique observation.

But of all observers in America and Europe the one who deserves the greatest credit for splendid scientific work, of the highest class, upon this comet, as well as being the (second) discoverer of its duplication was Matthew Fontaine Maury, the first director of the Naval Observatory at Washington, D. C. Yet one searches almost in vain to find his name mentioned in American astronomies of

the present day. How much of this is due to the deliberate attempt in the years following the Civil War to belittle his fame, the writer cannot say. However, he has never received anything like adequate recognition in this generation for his superb contributions to science from the country at large. Maury[1] measured the comet's position on January 12 but did not see the faint companion. This he discovered on January 13. In all 51 observations of the comet and 13 of the companion, on 29 dates up to April 19, were made at the Naval Observatory of which Maury personally made 49. This series was far the best secured anywhere in the world.

Let us quote from an original letter that appeared in part in *Monthly Notices*, Vol. 7, 90–91: ". . . . [Maury] discovered during his observations, on January 13th, a nebulous-looking object, altogether cometary in its appearance, preceding Biela's Comet by nine or ten seconds in the lower part of the field. . . . (January 14) both objects had increased about three minutes in right ascension since the night before. . . . . At the time of

[1] *Astronomical Jr.*, 1, 135.

the first discovery of their binary character, No. 2 was $\frac{1}{8}$ the magnitude, and $\frac{1}{4}$ the intensity of its companion. From that time No. 2 increased rapidly both in magnitude and brilliancy exhibiting, under the full moon of February 11, a sharp diamond-like point of light near its center. . . . . On February 16th, as I turned the telescope upon the comet in the early twilight of the evening, I was surprised to find No. 2 coming into the field with almost a blaze of whitish light (its color had been uniformly reddish), while Biela was barely visible. No. 2 was estimated to be equal to Biela as to magnitude, but to have one-third more intensity.

"The next evening was cloudy; and yesterday being clear, I tested their relative magnitudes and brilliancy again in the early twilight. The contrast was so striking. . . . . Biela surpassed his companion both in magnitude and intensity, at least twofold. . . . . Biela was brighter than it had ever appeared before. . . . . No. 2 had assumed its former muddy appearance, excepting that no bright point of concentrated light could be seen in its nucleus, notwithstanding the moon was absent, and atmospheric conditions favorable.

"No. 2 appears to have thrown a light arch of cometary matter from its head over to that of the other; and their tails stretching off below in the field, gives these two objects the singular and beautiful appearance of an arched way in the heavens, through which the stars are sometimes seen to pass."

The very complete notes of Maury on the physical changes are so important, and they give so much information on the disruptive forces in action, that they will be quoted at considerable length. The writer abridges the parts in parentheses.

"January 14. . . . were noticed glimpses of a tail to each body; (about parallel).

"January 18. Tail of Biela only a few minutes of arc long, extending to N. E. like a lancet. (Other's) not so long. Nuclei decidedly condensed towards the center, but not resolvable into points of light except perhaps Biela's by glimpses.

"January 23. Companion has the appearance of two tails, one nearly parallel to Biela's, the other reaching over to his nucleus or rather just to the south of it.

"January 28. Biela exhibited a pointed

nucleus; caught glimpses of a point of condensed light in nucleus of companion.

"February 4. A decided stellar nucleus to each comet, appearing like a sharp point of light. Tails reaching almost across the field and nearly parallel.

"February 11. The nucleus of companion decidedly stellar; that of Biela diffuse, and by no means as bright.

"February 12. Glimpses of two nuclei in Biela. (Tail $\frac{1}{3}$ field.) Tail of companion nearly parallel. . . . glimpses of another tail extending towards Biela . . . . in a sort of arch. Appearance of two tails to Biela, second going off in a direction opposite to companion.

"February 21. Ragged condensation of light in nucleus of Biela . . . . tails parallel.

"February 22. A band of nebulous matter, a little arched, joins the two. Appearance of a double nucleus about Biela. Has three tails radiating at angles of 120° to each other. The tail of Biela extends . . . . 45′.

"February 26. Biela has a tripod tail . . . . the one extending opposite to the companion very distinct. Confused appearance about

the nucleus of Biela as though there were several nuclei.

"March 5. Companion has no apparent nucleus; is exceedingly faint, and without any mark of condensation.

"March 8. One of Biela's tails points directly east—the other remains as it was.

"March 10. No stellar nucleus to either comet. No tail to Biela by the moonlight.

"March 14. Appearance of cometary fragments about Biela. Counted five in this position 

"March 17. Companion is a very diffuse mass of exceedingly faint nebulous matter. No appearance of fragments about Biela.

"March 21. Companion very faint, muddy; a shining point in a dim patch of light about its nucleus.

"March 30. Saw two tails to Biela as formerly. Companion not seen."[2]

E. Loomis wrote[3]: "From the preceding observations it will probably not be doubted that the two bodies had some connection with each other; that the one which we call Biela

[2] The notes above are original ones by Maury.

[3] *Silliman's Jr.*, *II*, 2, 437, 1846.

was the main body; and that the companion was formed of matter which proceeded from Biela. The question then arises, how did the companion become detached. . . . . Was there an internal explosion? Admitting the possibility of an explosion by which a cometary body might be torn in fragments, the rapid increase in size and brilliancy of the companion compared with Biela, from January 13 to February 16, seems hardly explicable except upon the supposition of a continued transfer of matter from one body to the other for an entire month. It seems then most natural to suppose that the cause of this continued transfer was the same as that of the first formation of the companion . . . . we have observed phenomena in other comets which have some analogy. . . . . Halley's comet at its last return was observed to emit streams of fiery matter, which exhibited the appearance of sectors of extreme brilliancy. The matter thus emitted from the head diffused itself in the direction opposite to the sun, and formed the tail of the comet. The attraction of these particles for each other was scarcely if at all appreciable. . . . . According to the rate of separation when first observed, these two bodies (Biela and

companion) must have been together about January 1. At this time we may suppose Biela's comet to have commenced emitting particles from its head, which uniting by feeble attraction formed a small nebulous body. Perhaps when the repulsive force began to operate, it may have been for a time resisted by an envelope partaking somewhat of the character of a solid body; and when this resistance yielded, a considerable portion of the main body may have been at once detached by a sort of explosion. A fragment thus detached might attract to itself at least a portion of the stream of particles which continued to be emitted from the main body. Thus the companion increased at the expense of Biela until February 16, which was soon after its perihelion passage. At this time the attraction of the companion was such that it could no longer attract to itself the matter repelled from Biela. It therefore ceased to grow, and indeed appeared to decline in brilliancy, perhaps from the loss of matter which it emits in the same manner as Biela; although we have an example in the case of Encke's comet of a body which habitually becomes less

conspicuous after rather than before perihelion passage.

"On the whole it must be admitted that the phenomena of comets are altogether anomalous. The comets of Halley, Encke and Biela, those of 1824 and 1744, have exhibited phenomena which seem to require us to admit the existence of matter of a different kind from anything we witness upon the earth."

Biela was followed elsewhere on this return by Hartwell in England until March 22, at Geneva until February 26, and at the Cape of Good Hope until March 7. As seen, Maury followed it at Washington with the 9-inch refractor there until April 19.

On the next return in 1852, the comet was first discovered by Secchi at Rome. The companion was in turn discovered by him on August 26, when he wrote: "I found this morning the other portion of Biela's comet. It was very faint, without a nucleus, ... ovoid form, the apex being turned away from sun. It followed the other part about 2^m, and was $\frac{1}{2}°$ further south. . . . . the principal part of the comet did not continue to appear of the same figure as at first. It looked quite irregular and had two very faint streaks; it was more

luminous in the center, but without any nucleus."

During this apparition, some observers measured only one component, some the other, a few both. On the whole it was found that they traveled about 1,500,000 miles apart, in similar orbits, so that it was difficult if not impossible to tell which of the two was the original comet of 1846. It was visible five weeks on this return.

The 1859 return was an unfavorable one for the comet's discovery, but not that of 1866. However, diligent search by many observers failed to detect the comet, nor has it ever been seen since.

But if Biela's Comet itself was not to reappear, the last had not been heard of this now famous body, though the rest of its history belongs more to the domain of meteoric astronomy. Yet as the débris of comets' nuclei evidently become meteors, it is clear that the two types of bodies merge into one another.

Schiaparelli having in 1866 finally proved the first case of connection between meteors and a comet—namely, the Perseids and Tuttle's Comet—it became common knowledge

how to proceed in similar cases. Therefore, the next year both Weiss and d'Arrest, within a few days of one another, announced that the meteors which have their radiant in Andromeda, and are hence known as Andromedes, and which since 1772 had at intervals furnished moderate showers, moved in the same orbit as Biela's Comet and were connected therewith.

D'Arrest predicted a shower for December 9, 1878, which did not occur, but Weiss making a much more thorough investigation proved that the node decreased very rapidly in longitude, and hence any future shower should come at an earlier date. He thought that there were good chances for a shower in 1872 or 1879, but that it would occur about November 28. A. S. Herschel, in England, asked all observers to be ready in 1872 and 1873 but did not seem to take seriously Weiss's work proving the regression of the node. Hence he still expected the meteors early in December.

Weiss, however, had his prediction brilliantly fulfilled for on the night of November 27, 1872, a wonderful display of the Andromedes —or as now usually called the Bielids—

appeared. For instance in Italy, at Moncalieri, four observers were able to count 33,400 meteors in the interval from $6^h\ 0^m$ to $12^h\ 30^m$. In many other places the rate for one observer was about 10,000 for the same interval. This display was seen in Europe, for by the time it was fully dark in America the Earth had passed out of the dense stream, and therefore only a moderate number appeared in the Western Hemisphere. These meteors, since they overtake the Earth, move with a low relative velocity. They also do not on the average appear as bright as those of the showers which come after midnight.

The appearance of this shower made Klinkerfues conclude that, if indeed we were then passing through the main body of Biela's Comet, the comet ought to be seen in exactly the opposite direction from the meteors' radiant point, as the former went away from the Earth. So he telegraphed Pogson at Madras, in India, as follows: "Biela touched Earth November 27. Search near Theta Centauri." Pogson at once found a small cometary looking body in this position. He saw it on two successive mornings, both times with a decided nucleus, and on the second with

a tail 8′ long. But cloudy weather then came, and he was unable to find it again once clear skies reappeared. No one from that day on has ever seen a cometary body moving in the orbit of Biela's Comet. Computations by Newton showed, however, that Biela's Comet itself must have been, on that date about 200 million miles from the Earth so the object seen by Pogson could not have been the comet itself. Newton considered it to be a fragment thrown off long before.

But Biela's history is not yet concluded for, in 1885 on November 27, another splendid shower of Bielid meteors appeared. It was estimated that from one place, if the whole sky had been watched by observers, about 75,000 per hour would have been seen. For instance Denza in Italy from $6^h\ 0^m$ to $10^h\ 08^m$, having with him from two to four observers, counted 39,546. The principal shower did not last over six hours, so the thickness was not great.

Again on November 23, 1892, a considerable shower from the same Bielid radiant was seen, this time in America. The rate however was only about 6 per minute, which shows that it had greatly decreased in intensity.

On November 24, 1899, the writer, as a boy, saw the expiring effort (at least to date) when a shower that attained a rate of 2 per minute came about 9 p.m. E. S. T. It did not last over two hours, and was of course seen by many observers in America. Meteors were also seen in Europe from the same stream that year. From then on only a few Bielids have been seen, in no case enough to dignify by the name of shower.

Even yet one more proof of its existence remains, for on the night of November 11, 1928, F. W. Smith, a student at Swarthmore College, Pa., while guiding on a region in Andromeda, saw and plotted 11 telescopic meteors, within a space of 102 minutes. He turned over his results to the writer,[4] who worked out an approximate radiant for 10 meteors, and computed a parabolic orbit. This fits, within reasonable limits, the orbit of Biela's Comet, showing that small débris from it was still being met by the Earth. Besides this unexpected meeting with these telescopic Bielids, we have had during recent November observations reported of single bright meteors whose paths go back to the old radiant.

[4] *Astr. Nach.*, 236, 15–16, 1929.

On the whole, we have here an excellent example of how a comet is broken up, with all the successive stages visible. First a comet of medium size and no special peculiarities returns several times. Then on one of its returns it wholly unexpectedly breaks into two parts, the division being caught even as it was in process of occurring, and being studied for weeks by many observers. On the next return, the companion comets went along their orbits side by side. On subsequent returns they could no longer be seen with any available telescope, though unfortunately at that time there was none of the short focus, powerful, photographic telescopes available, with which at present faint objects can often be detected when no eye can see them.

Then in 1872 the débris from the comet's orbit met us as a fine meteor shower, repeated in lessening intensity until 1899 when it died out. Now we see occasional isolated meteors, and a small group of telescopic débris.

We should indeed add that most of the meteor showers could not have been from débris of the comet as it was in 1846, but must have come from fragments broken from an original larger comet—the parent of both them

and the final Biela's Comet—many years before. Yet all were moving in approximately the same orbit, proving their original connection and common parentage.

Now, so far as we know, both comet and the condensations that gave the showers of meteors are wholly dispersed, and if a shower of any intensity again comes from this stream it will cause real surprise. There are well understood theoretical reasons[5] why this particular stream was liable to quick disruption, and would be shorter lived than, for instance, either the Perseid or Leonid groups.

[5] *Meteors*, 64–73; also 223.

CHAPTER IX

SEVERAL INTERESTING COMETS

"Nor so often did dread comets blaze."

—VIRGIL.

The Great Comet of 1858 was discovered by Donati at Florence on June 2.[1] It has since borne his name. When discovered it was $2\frac{1}{2}$ astronomical units distant from the Earth and was a faint nebulous patch without any remarkable condensation. About the beginning of September it became visible to the naked eye. It then had a tail which was 3° long on September 10, 12° long on September 27, and which by October 3 had grown to 36°. On October 5 the star Arcturus was transited by a portion of the tail, quite near to the nucleus. On October 9, a smaller tail was sent out, partly coincident with the larger, but having small brushes projecting from its convex side. The tail on October 10 was 60° long, 10° wide at end, and sensibly curved, the convex side being uppermost. The convex side was well defined, but the lower more indistinct.

[1] *Mon. Not.*, R. A. S., 19, 141, 1859.

As to its appearance in the telescope, Donati's Comet exhibited very beautiful phenomena, particularly in the development of concentric envelopes. On September 4, the nucleus was bright and well-defined; on September 11 the tail was 4°.7 long, and the nucleus was eccentrically placed within the envelope. On September 16, two diverging streams of light shot out from the nucleus and, after separating at the distance of a diameter from it and going for a short distance towards the head of the comet, they abruptly turned backwards and streamed into the tail. M. Rosa described it as resembling long hair brushed upward from the forehead and then allowed to fall on each side of the head.

On September 22 this "parting" gave place to a fan-like sector, surrounded by a darker arc, to which succeeded a brighter semicircle of nebulous light. On September 27 the fan was more spread out, while on September 30 its axis made a 25° angle with the axis of the tail. But about this date began also a new set of phenomena, namely circular or parabolic concentric envelopes, surrounding the nucleus. At first three distinct envelopes were visible, the outer diffused, the second better defined

and brighter, and the third (separated from the second by a less luminous interval) increased in brightness towards the nucleus, with which it was almost confused on the inner side. On the tail side sectors of 90° were missing from these envelopes, this space beneath the nucleus being very dark. Similar appearances were observed on October 4. On October 8 great distortions took place in the outer envelope. The next night an additional envelope appeared. These continued until October 15, when a new set of phenomena in the shape of "comma-like," curved appendages to the nucleus appeared. The latter seemed to eject a mass of brilliant matter in a straight line, which was by some other force violently twisted around. The "commas," variously modified, continued until October 22, when their extreme ends had so far turned back as to nearly complete an elliptically shaped body. On October 17 the nucleus was very eccentric with regard to the inner envelope, and somewhat less so with regard to the outer.

As for the envelopes, seven in all rose from the nucleus; the highest went out about 18,000 miles, the last about 6000 miles. The nucleus

showed the usual phenomenon of decreasing in both linear and angular size near perihelion.

The comet was followed in the Southern Hemisphere telescopically until March 4, 1859. From a ship[2] in the south Pacific it was last seen by the naked eye on November 11, 1858, and last with a 2.5-inch glass on November 16. From this same ship on October 11 the nucleus was estimated as being equal to a star of the first magnitude, while the tail was 8° to 9° long. The next night the nucleus was seen, after sunset, before any other stars in that region appeared. However, the comet was seen with the naked eye elsewhere[3] until December 9; hence it was visible without optical aid 112 days, with telescopic aid 275 days. The tail was seen for 177 days.

The comet passed perihelion on September 29, and was nearest the Earth eleven days later. Due to its position, near the latter date, the tail was not appreciably foreshortened, making the comet a magnificent object. Though its perihelion distance was about 50 million miles, this comet was remarkable for

[2] *Mon. Not.*, R. A. S., 20, 49, 1859.

[3] *Annals H. C. O.*, Vol. 3.

the brightness of its nucleus. Its orbit had a high inclination, 63°, and its period according to different computers was 1879, 2040, and 2138 years respectively. In any case it moves in a long ellipse, and will certainly return about the year 4000 A.D. A comet mentioned by Seneca, and dated in August 146 B.C., according to the Chinese, has been thought by some to be a previous appearance of Donati's Comet.

COMET 1861

The Great Comet of 1861 was discovered on May 13 by J. Tebbutt, of New South Wales, an amateur astronomer who did noteworthy work. Its perihelion passage took place on June 11, but it was nearly three weeks later before it was generally seen in the Northern Hemisphere.

Indeed it appeared with great suddenness to American and European observers on June 30 though seen by others the night before. It was described at New Haven[4] as being equal to Jupiter in total brightness, but with an area equal to the full Moon. It had a fine tail, with sharp, nearly parallel sides the extreme breadth being 10°. On July 2, while

[4] *Am. Jour. Sci.*, II, 32, 352, 1861.

the head was not quite so bright, the tail was 90° long. The head was 30′ in diameter. Near the center was a bright nucleus, from which emanated a luminous sector, with a 90° opening. On July 3, this opening was 136°. Beyond was a dark arch concentric with the nucleus, then a faint luminous envelope. Next came a fainter dark arch, and then a second fainter luminous envelope. The tail was 95° long, its axis deviating 12° from the line of the Sun. The tail broke off or became faint about 20° from the nucleus. From this point it continued as a much fainter milky band, decreasing gradually in luminosity, its breadth staying constant, at $1\frac{1}{2}°$. The breadth was 3° in brighter portion. The tail was apparently made up of two distinct streams of luminous matter, differing in width and length. The northern edges of the two were in the same line, but the extreme breadth of the shorter stream was much the greater. Its southern edge was badly defined, and somewhat concave outward. A very faint diffused light, rapidly widening, could be traced far beyond the point where the change in brightness occurred. After July 5 the tail decreased steadily in both length and brightness.

According to the Washington observation,[5] already on July 2, the tail had two branches. The first, slightly curved, was 8° to 10° long. The other, the wider or eastern branch, was straight and narrow, 1½° wide, and was 80° to 85° long. For the first 10° the tail was brilliant, then decreased in brightness. The nucleus appeared like a planetary disc a few seconds in diameter. Concentric envelopes, much like those of Donati's Comet were seen. On July 3 the nucleus was 11″ in diameter and elongated. Three days later the tail was 25° long, and on July 8 the nucleus was about magnitude 3.

According to Webb in England, who used a 5½-inch refractor, on June 30 the nucleus was brighter than Jupiter and 2″ in diameter. On July 4, he states it was only 0.5″, which is quite contradictory to the Washington observation of the previous night. Webb gives the coma as 20′ on July 4, and 13′ on July 15. On June 30 the comet was golden; on July 10 white to the naked eye, and greenish-blue in the telescope.

[5] *Am. Jour. Sci.*, II, 32, 305, 1861.

Chambers[6] states that eleven envelopes were seen to rise from the comet's head from July 2 to 19 inclusive, a new one rising every second day. Their evolution and dispersion therefore took place very much faster than in the case of Donati's Comet. Secchi stated that while the tail and parts of the head near the nucleus showed strong polarization, the nucleus itself showed no trace of it. But on July 3 and following days the nucleus showed decided indications of polarization.

About 6 p.m. on June 28, the comet's head was in the plane of the Earth's orbit, about 13 million miles distant on the inside. It seems quite certain that the Earth passed through the comet's tail on June 30, as has been discussed elsewhere (see p. 72). The difference in date can be easily accounted for by a very slight curvature of the tail, which is practically never an exact prolongation of the radius vector.

HOLMES'S COMET

This comet was discovered on November 6, 1892 by Holmes in London (1).[7] It was then

[6] *The Story of the Comets*, 157, 1910.

[7] *Observatory*, 16, 142, 1893. Also, *Handbuch Astr. & Geoph.*, 4, 25, 1893 and 5, 34, 1894.

5′ in diameter and a bright circular mass without nucleus. On November 9 it was a strikingly compact object, with sharply defined rounded edges. A complete change took place by November 16 when it was 10.5′ in diameter, and was markedly irregular in shape. After this a short, faint tail was developed. On a plate by Barnard on November 10 the comet's diameter was $\frac{1}{2}°$ and the tail 1° long. But during the middle of November the comet's transparency was so great that faint stars were seen through the densest parts. It was, however, visible to the naked eye. Its spectrum was meanwhile purely continuous, without a trace of bands.

By the middle of December the diffusion and decadence had continued so far that the comet was observable with difficulty, even in large telescopes. This increase in angular size took place despite the fact that the comet and Earth were rapidly separating. In January, the comet became brighter and smaller, but about January 16 it suddenly resolved itself from a scarcely perceptible mist into a nebulous star of magnitude 7 or 8, with a diameter of 30″. Coma and tail were entirely missing. On January 18 the stellar

nucleus was reported by Barnard as being barely distinguishable and of magnitude 13. By January 23 it was again 2′ in diameter and the object expanded into a dull nebulous mass, as before. On February 11, it was fairly conspicuous in a 10-inch refractor, but it had no stellar nucleus, instead there was a slightly condensed region in the head of the comet. During March it again became very faint, the last observation being made on March 13. It was, however, faintly visible until April. So long as it could be observed the comet had a continuous spectrum.

In 1899, the comet was found by Perrine on January 10;[8] it was then a round nebulous object 30″ in diameter with a faint central condensation, the total magnitude being 16. Its maximum light at this appearance was only magnitude 14. It was last seen November 6. Nothing happened to recall its strange performances in 1892. At its return in 1906, it was again excessively faint. It was not seen by anyone at the 1913 or any subsequent return.

Holmes's Comet has a period of 6.9 years.

[8] *Handbuch Astr. & Geoph.*, 11, 37, 1900.

Its orbit has an inclination of 21°, while the least distance to Jupiter's orbit is only 0.4 unit. It is considered to be a member of that planet's family.

TAYLOR'S COMET

Taylor's Comet, 1915*e*, another member of Jupiter's family, was seen on February 9, 1916, by Barnard[9] to have two nuclei, 10″ apart, while on former dates of observation it had shown only one. Both nuclei had short tails. For a time the north component grew fainter, the south brighter and more condensed. Then the north component brightened and showed strong condensation, while the south became diffuse and faint; finally the latter disappeared, leaving the north component a strongly condensed comet. Barnard stated that other comets which showed partition were: Biela's Comet, Comet 1860 (III), Great Comet of 1882, Brooks 1889 (V), Swift 1899, Kopff 1906, and Halley's Comet in May, 1910.

[9] *Mon. Not.*, R. A. S., 77, 355, 1917.

CHAPTER X

Morehouse's Comet

Comet 1908*c*, better known after the name of its discoverer as Morehouse's Comet, was discovered on September 1, 1908. Its orbit had an inclination of 140°, hence its motion was retrograde, and though it was observed for more than six months there was no appreciable deviation from parabolic motion. It passed perihelion on Christmas Day, hence it was well observed both as it approached the Sun and regressed. Its considerable perihelion distance of 0.94 kept it from approaching the Sun's vicinity, where violent changes in comets would be most probably expected. It was discovered by photography, but during part of its career was a naked-eye object, though never a brilliant one by any means, its maximum brightness being 5½ magnitude.

It was circumpolar for some weeks in the fall of 1908, and indeed traveled across the heavens before it disappeared. These favorable circumstances, coupled with the extraordinary phenomena which it exhibited, made

it one of the most observed and best known of comets.

Baldet[1] remarks that this comet might be called a blue comet, in contrast with Daniel's Comet of 1907—a yellow one. The latter was bright to the eye, but Morehouse's Comet could be photographed with relatively short exposures, and splendid results obtained. Neither the Swan nor cyanogen spectra extended, however, into the tail. Nor was there the slightest trace of hydrogen, despite an erroneous identification of that element.[2] The absence of the usual continuous spectrum in certain regions was also remarkable. Further the knots or luminous clouds thrown out by the nucleus into the tail had the same spectral constitution as the latter and *not* that of the head from which they emanated. Neither the Swan nor cyanogen spectra could ever be detected in the spectra of these knots. Baldet lists 82 radiations that he was able to detect in the spectra of this comet. Another interesting thing about the comet's spectrum was the doubling of a number of lines, the components being about 20 angstroms apart.

[1] Page. 24, *loc. cit.*

[2] *Astr. Nach.*, 179, 193, 1908.

This phenomenon was seen certainly as late as March 21, 1909.

Direct photographs recorded the strangest and most violent changes in the tail. The most remarkable occurred on September 30–October 1 and on October 15. The first transformation began between September 29 and 30 and ended the next day. The following account is abstracted from Prof. E. E. Barnard's article.[3] On September 30 a violent change was taking place through the night. On the previous night a plate already showed a disturbed condition in the comet. On the first plate of September 30, the head was small, and from this a thick tail ran out in a straggling manner with a fainter sheeting of matter having a sharp edge on the south side. On the next plate the whole tail had moved out bodily and was connected with the head by a very narrow tapering neck. The tail was wide and large, widening out very greatly as it left the head, being curved and brighter on the northern side. Fluffy masses projected from this north side. On the third plate, the tail had tapered down to a very

[3] *Astroph. Jr.*, 28, 292, 1908.

narrow connection with the head which was almost starlike. The fluffy masses had become a large projection. The tail appeared cyclonic. Doubtless an hour or so later the whole tail had become disconnected from the head, as the separation is essentially shown on the last plate. A similar separation was shown on a plate of September 20. The first plate on October 1 showed what was evidently the great mass of matter which formed the tail on September 30, now about 2° out from the head. The tail was 8° long. The outer 6° of this was made up of an irregular, long, straggling mass which had a tendency to spread northward. This great mass was apparently attached to the head by a slender thread. There was a narrow, short ray from the head, at a 45° angle on the south side.

On the second plate two rays connect with the great mass, one of which after running parallel with the main one for a degree, bends in and joins it, making only one ray that reaches the head. On the third plate a diffused ray had shot out for 1° on north, while there were several streamers connecting the mass with the head. On the fourth plate, the new ray had merged. On the fifth, the new

rays curved northward and joined the system of rays from the head at a distance of 2°. The outward end of a ray system had become disconnected from the great mass, which had become square in form and now sharply defined at the end nearer the head. On the sixth plate the separation was complete and the end of the great mass more pointed.

On October 2 the comet had a changing system of broad curving streamers spreading out at wide angles. On October 3 the tail consisted of a widely diverging skeleton framework changing rather slowly. On October 4 the tail had become a normal one again.

On October 15 the first plate showed a straight narrow tail $\frac{1}{2}$° long, with short rays out from the head at angles of 30° and 45°, on either side. At the end of the $\frac{1}{2}$° tail began a most unusual tail which was twisted and clouded at the beginning and which streamed out irregularly, bending northward with irregular outline for 7° to 8° to the edge of the plate. On the first plate the straight tail joined the south portion of this twisted mass, and in the last picture of this date it made a junction further north at about the middle of the mass which was $\frac{1}{4}$° broad where it began.

These masses were very dense and, from the south part, narrow streamers ran out parallel with the short tail for about 2°. In the photographs of October 14 there were no indications of this disturbance. Remnants of these cloud masses were shown much farther out on plates of October 16 and 17. However[4] on October 15 plates were taken at Geneva and Juvisy, 8 hours and 7 hours respectively earlier than Barnard's first plate of that date. On the Geneva plate about 20′ from the head there was a strong bend in the tail but no masses. On the Juvisy plate this bend was stronger and more suggestive of the appearance later shown on Barnard's plate. The latter therefore concluded that the masses were not thrown off as such from the comet, but had their origin in a disruption of the tail which must have occurred just previous to 7^h G.M.T. Barnard said this concurred with his idea that comet tails encountered some sort of disturbing medium in space.

The variations in the appearance of the comet were the most rapid ever observed. Many times photographs, taken at one day's interval, appeared so different one would not

[4] *Astroph. Jr.*, 29, 70, 1909.

know that they belonged to the same object. One fact was clearly established, namely, that the formation of the tail was intermittent and not continuous. The formation of parabolic envelopes on the side towards the Sun was most striking. Eddington[5] says that the envelopes in the Greenwich photographs were for the most part sharply defined, fine curves, differing markedly from similar appearances in other comets. He considered that each envelope corresponded to a distinct explosion, while in other comets the explosions were so numerous that only a general effect was noticed. Here the individual envelopes were all most transitory, and immediately after their formation began to collapse and shrink. None expanded. After three or four hours an envelope had completely degenerated, the part between the nucleus and the Sun being lost in fresh material rushing out, which would form new envelopes, that behind mingling with the tail. Envelopes on contracting were more sharply defined. The size therefore seemed to depend on the age. He concluded that, if we accept the simple theory of the formation of envelopes, i.e., that they are formed by jets

[5] *Mon. Not.*, R. A. S., 70, 444, 1910.

from the nucleus, then the repulsive forces must be from 10 to 100 times as great as those that act on particles in the tail.

Barnard noted that parts of the tail suddenly brightened up where apparently no material previously existed, and with no visible supply coming from the nucleus. An explanation was that such knots or condensations in the tail were due to the superposition of detached rays or band crossing one another, giving rise to increased brilliancy at their intersection points, and shifting with the relative positions of the rays.

In the Southern Hemisphere, the comet could be seen by the naked eye as late as March 13, 1909. On March 3 the tail was 3° long, and on March 13 was 1° long and nearly severed from the head. Another observer with a 9½-inch telescope on March 17 saw the comet as very bright, with head large and condensed in center surrounded by a faint sheen with fan-like streaks. The tail was straight, 2° long, and fairly well defined. The comet was traced in a 10-inch reflector until April 15, when the coma was broad and diffuse. The tail was 20′ long, broad and very faint. With the same instrument it could not be seen on May 10.

CHAPTER XI

Pons-Winnecke's Comet

This comet was discovered by Pons on June 12, 1819, and rediscovered by Winnecke in 1858. It has been observed at the following returns: 1819, 1858, 1869, 1875, 1886, 1892, 1898, 1909, 1915, 1921 and 1927. The comet's orbit has a small inclination, belongs to Jupiter's family, and undergoes very great perturbations from Jupiter. It also comes near the Earth's orbit. Table 12 illustrates the great changes in its elements on several of its returns.

It will be noticed that its period is almost exactly half that of Jupiter's (11.86 years), which has made investigations of its orbit of particular interest. This has, indeed, been the subject of a very great deal of study on the part of many astronomers, and will doubtless continue to be for many future returns. The comet has never shown a tail, a circumstance due almost surely to the fact that all tail-forming material has long since been expelled. This is a phenomenon quite general with comets of Jupiter's family, which per-

force approach the Sun at such short intervals of time.

As the comet is a relatively inconspicuous object, and presents no special features of interest other than changes in the orbit at different returns, we will pass over accounts of its earlier appearances, and begin with that

TABLE 12

CHANGES IN THE ELEMENTS OF THE PONS-WINNECKE COMET

YEAR	a	e	q	i	π	Ω	P
1819	3.160	0.756	0.774	10° 43′	274° 41′	113° 11′	5.62y
1858	3.137	0.755	0.769	10 48	275 39	113 12	5.56
1898	3 242	0.715	0 924	17 00	274 14	100 53	5.84
1909	3.262	0 702	0.973	18 17	271 37	99 21	5.88
1915	2 825	0 701	0.972	18 18	271 43	99 23	5 87
1921	3 297	0 684	1 041	18 55	268 24	98 06	5.99
1927	3.305	0.686	1.039	18 56	268 32	98 09	6.01

of 1915. The reason is that in June, 1916, when the Earth was nearest the comet's orbit, though the latter had passed by nine months before, a meteoric stream of some intensity was met, which traveled in almost the same orbit as did the comet. This circumstance brought greater attention to the comet, which has not diminished at subsequent returns. Something further will be said of the accompanying meteors at the end of the chapter.

In 1915 the comet was detected by photography at Bergedorf on April 4, by Thiele; its magnitude was 16. Passing perihelion on September 1, it came nearest the Earth on September 24, but it was a faint object, being more than a unit distant. At Johannesburg on November 8, it was described as 20″ in diameter and of magnitude 12.

In 1921, Barnard at Yerkes found it on April 10, when its magnitude was 12. It brightened rapidly until it was 6.5 magnitude in June. On this return, for the first recorded time, its perihelion fell *outside* the Earth's orbit (see table 12). This was due to enormous perturbations by Jupiter which increased the perihelion distance about 5 million miles between the 1916 and 1921 returns.

On the 1927[1] return the comet was detected by van Biesbroeck at Yerkes Observatory on March 3, though later it was found on a Greenwich plate of February 25. Its magnitude was 15 or 16. By April 9 the comet was about 9½ magnitude, diameter 6′ or 7′. There was a central condensation, which was not stellar, of magnitude 11. On May 2 it was

[1] *Obs.*, 50, 127, 1927.

circular and 5′ in diameter. The central 15″ was much brighter. The nearly stellar nucleus was magnitude 12–13, the total light equaled a 9½ or 10 magnitude star. But on May 3 it was down to magnitude 11. On May 20 it was about 9′ in diameter, with a nucleus of magnitude 11. The inner coma was brightest in the second quadrant suggesting a broad streamer emitted in that direction by the nucleus. No tail was seen, however. During June, when the comet came nearest the Earth, its total light equaled magnitude 4. The nucleus was sharp and well defined. Steavenson, using the Greenwich 28-inch, a few days before the date of nearest approach, observed the nucleus as practically stellar and about 1″ in diameter. The comet on June 26.7 came within 3.6 million miles of the Earth, a record broken only by Lexell's Comet in 1770,[2] which came to within 1.5 million miles, when its apparent diameter was 2½°. During this period[3] Baldet at Meudon estimated the diameter of the nucleus as less than 1 km., and Slipher at Flagstaff as about 2 miles. The comet, during June, traveled

[2] Chambers, 39, 87.
[3] *P. A.*, 35, 412, 1927.

down the Milky Way, from north to south, and in general appeared as a round hazy spot about 1° in diameter. The nucleus equaled a 9 magnitude star. From it emanated a narrow pencil of light towards the Sun, which gradually spread out fanwise. The comet resembled in brightness and appearance the Nebula in Andromeda as seen by the naked eye. During the latter part of June it moved many degrees per day traveling 106° across the sky from June 10 to July 2. By the end of the month it had gone too far south for successful work by observers in the Northern Hemisphere. The comet was, however, observed at Johannesburg until December.

Objective prism plates at Yerkes Observatory showed main condensations due to C IV, C + H, and Cy IV, though the details were diffuse. At the Lick Observatory[4] on June 23, a one-prism spectrograph attached to the 36-inch refractor secured a strong spectrum of the comet, with an exposure time of 5.4 hours. The comet that night had a very sharp stellar nucleus of 9.5 visual magnitude. Extending from it east of north was a bright

[4] *Pub. A. S. P.*, 39, 222, 1929.

fan-shaped jet or streak. The spectrum, extending from λ3900 to λ5000, appeared to be the usual solar spectrum with the carbon and cyanogen bands superimposed. Both the carbon and cyanogen bands are much fainter and the Fraunhofer spectrum of the nucleus is much stronger than in the spectra of bright comets. Such a spectrum is similar to that of other short period comets, and is in harmony with the opinion that such bodies have largely lost their gaseous material, due to numerous returns to perihelion.

Slipher at Flagstaff reported that the "spray of light" appeared to be more emissive than any other portion of the comet. The nucleus appeared sharp and only 2 or 3 miles in diameter, but on one or two occasions faint secondary condensations were seen. These latter led others to question whether the nucleus represented the exact center of mass of the body. Thiele suggested that perhaps a rotation of the nucleus around this hypothetical center of mass might explain some of the anomalies and difficulties found in computing an exact orbit from the observations.

Baldet[5] using the great Meudon refractor

[5] *Bul. Astr. Soc. de France*, 41, 401, 1927.

of 0.83 meter aperture, made extensive observations when the comet was nearest. He states that the nucleus was a stellar point, almost at the limit of visibility, perceptible only with high power and in good seeing. It was surrounded by a circular nebulosity 2″ to 3″ in diameter (which would correspond then to from 60 to 90 km.) which was sharply detached from the coma in general. The nucleus proper must have been less than 5 km. across. In his opinion the nucleus could only have been one solid body, for he says that a swarm of corpuscles submitted to the various perturbations and the expansion of the included gases would have been dispersed. He found the nucleus of magnitude 13, but it with the gas around it—which would all appear as the nucleus in a smaller telescope—to be of magnitude 10. From photometric considerations he derived 400 meters as the probable diameter of the solid nucleus. The total diameter of the coma, determined with the naked eye, was about 300,000 km. Photographs did not show so large a value. The brightness of the whole was 4 or 4½ magnitude.

He adds that the attraction of the nucleus upon the surrounding gases could not hold

these, as a planet does its atmosphere. Therefore this gaseous envelope must be constantly lost and as constantly renewed. This seems to be done by jets, great and small, coming out of the nucleus and oriented toward the Sun.

A glance at the table of elements shows that at the 1909 return the perihelion distance had already approached unity. So far as the writer knows, though he has made no search to check his memory, no meteors were seen in 1908–1910 which were then considered to be connected with Pons-Winnecke's Comet. However, about fifteen years later when the fact of the great fall of meteorites in Siberia, which took place on June 30, 1908, was authenticated, Meltzev calculated that these meteorites probably followed the orbit of the comet and were connected therewith (see p. 203).

However, the discovery of a meteor shower in connection with this comet was made in June, 1916. Quite a bright shower was seen by W. F. Denning and others on June 28, the meteors coming for a time at the rate of one every minute or two. Previously, late in May and early in June, numerous meteors

were seen in America. Their radiants gave parabolic orbits[6] which fitted the comet's orbit approximately. The radiant of the bright shower on June 28.5 G. M. T. also coincided with that of meteors in the comet's orbit. The connection of these meteors with the comet was thus plain.

In 1921, as the comet's perihelion had meantime continued to move outward, there was much uncertainty as to whether the accompanying meteor stream had passed on too far to be cut by the Earth's orbit. Nevertheless a shower was carefully looked for, with entirely negative results in both Europe and America. Only from Japan[7] came the account of a strong shower, made up almost wholly of meteors below magnitude 5. Nowhere else was this confirmed.

In 1927, the comet itself passing so very near the Earth, there was a much better chance. Observers everywhere were asked to be on the lookout. But again general results were disappointing. Indeed reports were so contradictory that it is difficult to know what did happen. From Russian Turk-

[6] *Mon. Not.*, R. A. S., 77, 71, 1916.
[7] *Mem. Kyoto Impr. Univ.*, V, 5, 1922.

estan came an account[8] of a strong shower, again of faint meteors. In America in isolated localities many meteors were reported, but places a few hundred miles away saw almost none. It is, however, certain that many fireballs did come at the critical epoch, some of which doubtless belonged to the comet's débris. One that appeared over Tennessee on June 27 at 14^h 22^m 37^s C. S. T. had its orbit computed by the writer.[9] The elements, which were rough, rather resembled those of the comet's orbit. A wonderfully bright fireball[10] photographed in Manchuria by Yamamato on June 29, 1927 at 15^h 51^m G. M. T., was considered to be a member of the comet's family.

However, from what we know of similar meteor showers the writer is forced regretfully to express the opinion that the chances are against its reappearance in strength, rather than in its favor. This is due to the fact that already the perihelion point has been shifted beyond our orbit. Unless perturbations in future shift it back, we will probably see fewer and fewer of these meteors in coming years.

[8] *A. N.*, 232, 283, 1928.
[9] *P. A.*, 37, 343, 1929.
[10] *P. A.*, 36, 496, 1928.

CHAPTER XII

Comet 1910*a*

"Cosi Beatrice: e quelle anime liete,
Si fêro spere sopra fissi poli,
Fiammando forte a guisa di comete."
—Dante.

This comet was discovered about the middle of January, in South Africa. It passed perihelion on January 17. After this it rapidly moved northward, and at first it was hoped that we would have the opportunity of seeing a really great and brilliant comet. This hope was not fulfilled however, though the comet for a few days was a bright and conspicuous object.

At the Lick Observatory, where the writer then was, a search was made for the body on the afternoon of January 17[1] but it was not found. Next day it was plainly seen about 11 a.m., 4° east of the Sun and much brighter than Venus, which was easily visible 30° away. The comet had a short tail about 1° long, which was also easily seen with the unaided eye. Visual observations by Wright[2] showed

[1] *Pub. A. S. P.*, 22, 29, 1910.
[2] *Lick Obs. Bul.*, 174, 1910.

the spectrum of the nucleus to be continuous, crossed by the bright D lines, extending 12″ to 14″ out into the coma. With a 6-inch telescope, the nucleus appeared very small and bright, with a sharply defined edge, with no gradual shading off into the coma. Streaming back from and surrounding it were nebulous envelopes, traceable for $\frac{1}{2}°$. Next day, i.e., January 19, efforts to locate the comet in the daylight sky were fruitless and, at dark, clouds came up that lasted until January 26.

Plates were taken by Paul W. Merrill and the writer with the Crocker 6-inch telescope on January 26–30 inclusive and on February 1. The nucleus, as seen on these plates, on January 26 was sharp, on January 27 it was elongated N and S, and on January 28 and 29 round. As for the tail it was trifurcated on January 26 to within 6° from the nucleus. On another plate, with the nucleus off the plate, 14° of it could be traced, with a great fork at 13° from the nucleus. The trifurcated tail could be traced 8° on one plate on January 27, with 11^m exposure. The great fork plainly shows on another plate, having 14° of the tail on it. On January 28 the southern branch was relatively stronger, 5°

of the tail being photographed. On January 29 the great fork still showed plainly, 14° of the tail being on the plate. On January 30, with hazy sky, the tail was faint and short. On February 1, the tail was 2° long, with the southern branch relatively stronger. Narrow, sharp streamers and bright knots or condensations nowhere appeared. The southern branch, which made a smaller angle with the radius vector than the others, did not extend so far from the nucleus in proportion to its strength. It, however, while diminishing daily in absolute intensity, gained in relative intensity.

As to the visual observations on these same nights, the tail was seen to be from 15° to 30° long. On January 27, Aitken described it as in "the form of a long feathery plume, curving slightly toward the south from a vertical direction, until it reached a point about 15° from the head; then the tail forked, and the curvature toward the south of the main part became, rather abruptly, very much more pronounced. This branch could be traced at least 15° further. The northern fork could only be traced 2° or 3°."

Curtis photographed the comet with the 37-

inch Crossley reflector on February 1, 2 and 5. On the plate of February 1, the head proper was very bright, round, without apparent nucleus, and slightly over 1′ in diameter. Numerous streamers radiated from the head, but no knots or condensations were shown. Albrecht with the 36-inch refractor and a grating spectrograph, using sodium flame as a comparison spectrum, photographed the D_1 and D_2 lines. The second was bright, on the plate. The D_1 line was faint. Measures of D_2 gave R. V. = 63.3 km/sec, while the computed R. V. was 62.7 km/sec. The weighted mean of D_1 and D_2 was 66.1 km/sec.

Wright observed the spectrum visually on January 26, finding "some continuous spectrum and a number of bands, probably the regular cometary bands, also a bright line in the orange, undoubtedly the D lines, blended." A plate taken at same time showed faintly the bands and D line. On January 27 he says: "the three bands present, also D line. There is a pronounced brightening just to the red of D." On January 30, the D lines were no longer visible, but the brightening in the red was faintly seen.

The comet, having switched to the morning

sky, was seen during the early part of March being of magnitude 8 on March 12. During the first few days of its appearance as an evening object, several observers had estimated its head as being of the first magnitude. Barnard[3] with the 40-inch Yerkes refractor measured it up to June 12. He saw the comet on April 12 as "faint, feebly condensed; 13th or 14th magnitude, rather large; no nucleus or elongation." On June 7: "There is a slightly brighter portion 5″ in diameter. The whole is perhaps 15″ in diameter and the brightest part 16th magnitude." On June 12: "Very faint. It diffuses over perhaps ½′ or more. There is a more condensed portion 5″ diameter and 16th magnitude."

Aitken on April 16, with 36-inch Lick refractor, saw the comet as of 12 to 12½ magnitude, with feeble condensation and indefinite boundary.

Baldet found that the spectrum of the comet was very unique. The tail gave, for a length of 8°, a continuous spectrum. But the dispersion was small, 7 mm. from λ4740 to λ3880. This was not at all like the spectra of the tails

[3] *Astroph. Jr.*, 26, 137, 1910.

of Daniel's Comet and Morehouse's Comet, at least up to $\frac{1}{2}°$ of the nucleus. Very near this latter in three places were feeble prolongations which perhaps could be identified with it. The nucleus gave an intense continuous spectrum upon which were detached images of the head, of which the most brilliant was the blue band of the Swan spectrum. Baldet had plates taken on January 22, 29, and 30; only for the middle date was the plate satisfactory, due to poor observing conditions.

Sodium rays were seen from the first day of discovery; then they rapidly diminished in intensity while the Swan spectrum became more and more brilliant. The variations resembled those of the Great Comet 1882.

Newall with a direct vision spectroscope saw the comet almost entirely in sodium light on January 22. "Then as the comet left perihelion, which had taken place on January 17, the sodium image became both more feeble and less extended, up to when it was emitted only by the nucleus. The usual green image was emitted only by the nucleus also. On January 22 at Meudon with an objective prism the sodium image was photographed to within 20′ from the nucleus. Here also was

obtained an image in the red.[4] From the side of the extreme red, the continuous spectrum showed a very short reinforcement from λ620 to λ700, which prolongs into the tail for 10′, and which perhaps belongs to a group of intense bands common to the nucleus and to the tail, and not noticed in other comets."

As to the origin of these it is uncertain. They might be due to the red spectrum of cyanogen.

There was great trouble in determining the orbit of this comet. The several preliminary orbits published differed widely from one another. As an example, the first three gave the inclination as 62°, 85°, and 57° respectively. A correct orbit finally gave it as 139°, entirely reversing even the direction of motion! Its perihelion distance was $q = 0.13$. No decided deviation from a parabola could be found.

The reason that the comet was not discovered until it was a brilliant object was, as usual, that in coming toward the Sun it had kept, as seen from the Earth, in the very near neighborhood of the former body.

[4] *C. R.*, 150, 254, 1910.

CHAPTER XIII

Comets and Meteor Streams

"And the stars shall fall from heaven even as a fig tree casteth her untimely fruit when shaken by a mighty wind."

Having outlined the various theories of the behavior of comets which are typical or appear worthy of mention, we shall now give the connections that have been proved between comets and meteor streams, and between the orbits of comets and certain other bodies. The writer believes that only in view of these connections and analogies can we hope to secure a comprehensive view of the questions at issue. All references here to mere opinions will be omitted and the discussion will be limited to facts which are accepted generally.

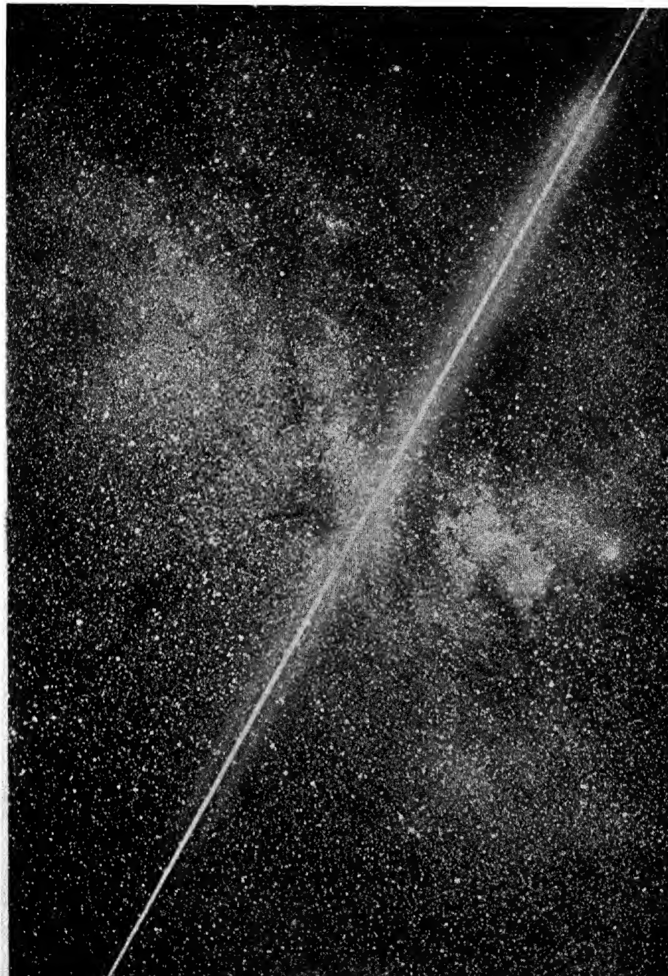
In 1866 Schiaparelli[1] proved that the Perseid meteors, which now come to a maximum about August 11 each year, move in the same orbit as Tuttle's Comet (Comet 1862 (III)). In 1867 Peters similarly announced that the Leonids, the meteors which furnish

[1] *Meteors*, Chapter IV.

the great showers every thirty-three years, follow the same orbit as Tempel's Comet. Shortly afterwards similar connections were proved for Biela's Comet and the Andromedes or Bielid meteors; and for the April Lyrids and Comet 1861 (I). Since that time it has been proved that the May Aquarids move in nearly the same orbit as Halley's Comet (p. 125), and a shower of meteors has been connected with Pons-Winnecke's Comet (p. 175). In addition a few other minor showers have been announced as following in the same paths as various comets, but so far these cases rest on slender evidence, and are scarcely considered as proven.

These facts lead at once to the conclusion that there must be a very close connection between certain comets and meteor streams which are either annual or at least periodic in character. Being the one best known, the Leonid system will be discussed here as an example.[1]

A search of old records has shown that brilliant meteoric showers have been coming ever since the year 902 A.D., at least, at times of the year which correspond now to the middle of November. The interval between



THE GREAT BOLIDE OF AUGUST 13, 1928
Photographed by M. de Kerolyr at Astrophysical Station of Haute-

successive showers was usually thirty-three years though sometimes the showers came more than one year in succession. As stated, when the orbit of these meteors was calculated, it proved to be the same as that of Tempel's Comet.

In records previous to 1800, there is little or no mention of meteors on nights preceding or following the one on which the great shower appeared. We are hence unable to make any deductions as to the total width of the Leonid stream at these returns. Attention had been sufficiently focused upon such matters by about 1860 for records to be made on several nights. We thus know that some Leonids appeared at least a day earlier or later than the maximum date. By the 1899 return the writer had begun personal work, so that he can state on his own authority that from 1900 on one might see Leonids on as many as four successive dates at least. Careful observations in 1928 and 1929 show that Leonids may be seen over an interval of nine days. But it is impossible to conclude with certainty from this that the Leonid stream has doubled its width in the past half century or so. It probably merely means that there are

more observers, who work on more nights than formerly.

Be this as it may, we can picture the Leonid stream about as follows. The major axis of the orbit is 9.5×10^8 miles long, or 20.68 astronomical units. Its eccentricity is 0.90, so the orbit's major axis is 2.29 times as long as its greatest width, i.e., its minor axis. Let us now take the inner tube of an automobile tire and bend it into such an ellipse. Put the Sun at one focus, and have the diameter of the tube equal to the distance that the Earth goes in passing through the stream each November, making due allowance for the crossing not being at right angles. Now consider the tube sparsely filled with meteors, all moving in the same direction, and taking $33\frac{1}{4}$ years to make a complete journey from perihelion to perihelion again. But for a part of this stream of such length that it takes three years to pass the Earth's orbit, as it comes towards the Sun, the meteors are much more closely packed, and in the very middle of this "three-year section" packed very closely indeed.

The Earth passes through this tube about the middle of each November, usually meeting

only the sparsely scattered Leonids. But at 33- or 34-year intervals it goes through the dense part and for three or four years we have much finer showers. And if, as in 1799 and 1833, the Earth happens to hit the very dense part the "gem of the ring" as it is sometimes called—then we have a grand meteoric shower.

Nevertheless we must confess that on some of the proper dates, as for instance in 1899, no rich shower occurred. We can only infer the reasons for the various blank dates during the past one thousand years, but in the 1899 case the cause is well understood. This is scarcely the place to enter into technicalities about meteor streams, so all that need be said is that, as the group which should have met us in 1899 was on its way Jupiter happened to be in that part of its orbit very near the meteors' orbit. Its great perturbations sufficed to switch the main stream aside enough to miss the Earth, as it passed us in 1899. But Jupiter having moved on before the 1901 group passed his orbit, these Leonids gave us quite a respectable, if not brilliant, shower in November of that year.

If it is asked whether another grand shower will come in 1932, 1933 or 1934, or for that

matter in each of these years, as yet no definite answer can be given. It all depends upon the perturbations suffered by the main groups of Leonids in the past thirty-three years. No one appears to have attempted to calculate these perturbations, which present a most troublesome problem. So far as an off-hand opinion goes, the meteor stream meantime may have been switched either toward or from us. In the first case we should see a really fine shower, in the latter next to nothing. We simply do not know yet what to expect.

Coming now to similarities between the orbits of comets and those of other bodies, let us first discuss the asteroids. These are numerous small bodies, about 1500 being already known, nearly all of whose orbits lie between those of Mars and Jupiter. They vary in size from Ceres, whose diameter is 480 miles, to the smallest so far discovered which may be of the order of 5 miles or less. Smaller ones certainly exist, but are too faint for ready discovery. Doubtless there is *no* limit to their size, which may range on down to mere particles of matter like meteors.

Leaving out a few exceptional cases, they do not seem to penetrate inside the orbit of

Mars or go appreciably outside that of Jupiter. But to discover objects 50 miles in diameter or less would be almost hopeless if they were outside Jupiter's orbit. Few of the known asteroids are so large. Hence there is neither proof nor good reason to assume that asteroids do not exist between

TABLE 13

ASTEROIDS WITH EXCEPTIONAL ORBITS

	719 ALBERT	887 ALINDA	944 HIDALGO	945	1924TD	1927BD
a	2.58	2 53	5.71	2.6	2.66	10.66
e	0.54	0 53	0.65	0 16	0 54	0.76
i	10.8°	9.0°	43 1°	33.0°	20 1°	6.0°
P	4.12y	4.2y	13.7y	4.3y	4.35y	34.8y

Jupiter's and Saturn's orbits, or perhaps even farther out from the Sun.[2]

All of these objects so far discovered move with direct motion, and many of them in orbits of moderate eccentricity and inclination. But there are some most exceptional cases, of which a few will be quoted (see table 13). If we compare these orbital elements

[2] For a modifying opinion see, however, E. W. Brown, *Resonance in the Solar System, Bul. Am. Math. Soc.*, May–June, 1928.

with those of the short period comets we find many striking resemblances. In fact many of these comets' orbits have much less inclination and less eccentricity than have the asteroid orbits mentioned. This would mean that such an asteroid, if it showed a coma or tail, would be classed most certainly as a comet. Where then is the dividing line?

However, the question can be more properly discussed—in all its various phases—in the next chapter, so only this preliminary sketch will be given here.

The mass of literature on comets is so great, and in so many languages that the writer is unable to state who was the first seriously to suggest possible connections between asteroids and comets. The idea was, however, somewhat fully outlined by him in 1924.[3]

[3] *Meteors*, 264–272.

CHAPTER XIV

Collisions of Comets with the Earth

"And there fell a great star from heaven, burning as it were a lamp. And it fell upon a third part of the rivers. . . . ."

One day a few thousand years ago, a frightful apparition appeared in the heavens over the western part of what is now the United States. A tremendous blazing mass shot downward through the sky with terrific speed from north to south. As it came lower it was surrounded by smoke, and it looked something like the blackest of storm clouds. The roar was terrific and the air waves set up by its passage were felt far and near. Finally, with a crash that exceeds description, it struck a semi-desert part of what is now Arizona. Instantly into the air arose a gigantic column of débris and rock dust, while on the borders of the immense crater pit formed by the impact were deposited masses of shattered rock of all sizes falling back from the sky. A violent earthquake, which however was over very quickly, spread further consternation among all the tribes on or near

the Pacific Coast. Had there been forests anywhere within miles of the crater the sideways rush of the super-heated and compressed air would have laid them level with the ground, as indeed it would have done to any human habitations. Every wandering animal and any chance hunter or traveler who happened to be near was, of course, instantly killed. But the catastrophy was almost instantaneous; in a few seconds all was over, and ere long even the air was still once more. The silence of death and desolation remained there for centuries thereafter, because the Indians held the spot to be holy and they dared not approach it. For had not a god descended from heaven to take up his abode in the crater?

But as years went on white men arrived, who had no fear of sacred places. They saw the great crater and wondered at it. And it was noticed that many strange masses of iron lay scattered for some miles around. Some of these eventually reached the hands of scientists who identified them as meteorites. As meteorites have a commercial value many hundreds were then collected and sold far and wide. So that the "Cañon Diablo" meteor-

Effects of the Great Siberian Fall of Meteoric or Cometary Fragments, June 10, 1908
Photographed by L. A. Kulik; courtesy of *The American Weekly*

ites as they are called are probably the most widely distributed of any.

The great excavation of which we have been speaking is now generally known as "Meteor Crater." Briefly it is a hole with very steep or almost precipitous sides, nearly round, and 4200 feet in diameter. The rim, made up of débris of all sizes, rises about 125 feet above the plain. Inside the depth is about 500 feet, but this does not measure the depth of the hole, for the bottom is filled by broken masses and rock-flour to an additional depth of 650 feet.

The immediate neighborhood is non-volcanic and the rocks, which consist of limestones and sandstones only, lie in horizontal strata. Around the crater, on the outside, many meteoric masses were found, some as much as 4 or 5 miles away. The largest of these weighed several hundred pounds. In the rim were found numerous iron shale-balls, as they were called. Some of these were also found mingled with the débris inside. Practically no meteoric material of any size was found mixed in the rock-flour at the bottom, though many shafts were sunk there. The exposed strata on the inside slopes are all

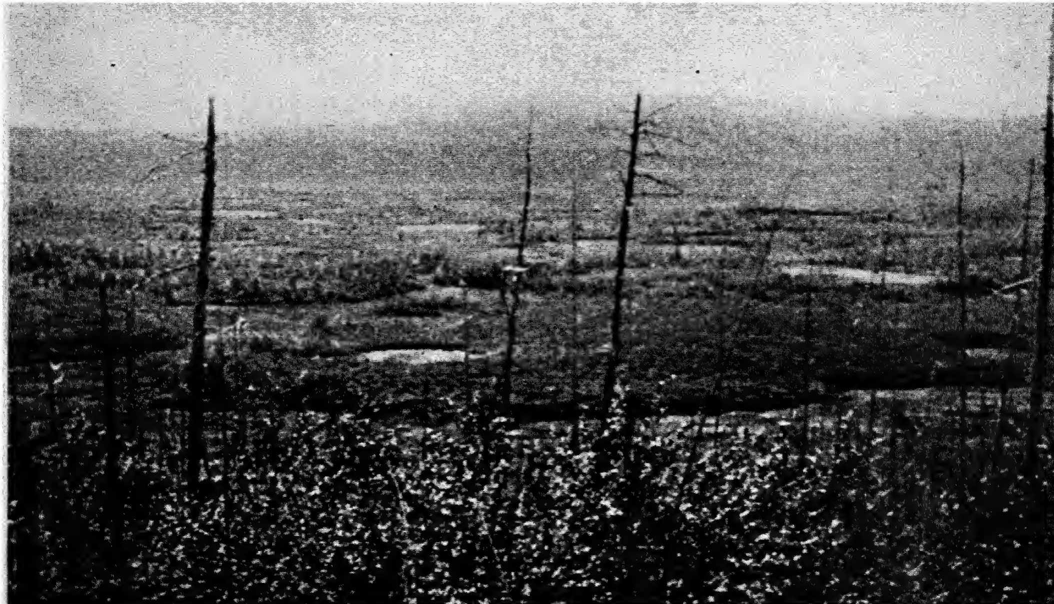
horizontal except on the south. Here there is a considerable arch, inferring something had forced the strata upward at this point.

Once scientists had visited the crater, theories of its origin were advanced. At first the opinion was held that it was explosive, i.e., volcanic in origin. This was put forward by eminent men[1] and went almost unchallenged until about twenty-five years ago. However, in 1905, D. M. Barringer of Philadelphia, a mining engineer, who was also a scientist, after close study published[2] his conclusions. In these he advanced an impact origin due to a great meteoric mass. At first his views met with little favor, even violent opposition. But as time went on further work proved him correct most conclusively.

Finally in 1920 a drill-hole, right through the top of the arch mentioned, struck meteoric material over 1300 feet down. There is every reason to believe the main mass lies buried there. Mining operations are now in progress with a view to recovering the main body. Analysis of fragments show the usual iron-nickel composition, but also enough platinum

[1] G. K. Gilbert, *Science*, 31, 1896.

[2] *Proc. Acad. Nat. Sci., Philadelphia*, lviii, 881, 1906.



Craters Made by the Great Siberian Fall of Meteoric or Cometary Fragments, June 30, 1908
Photographed by L. A. Kulik; courtesy of *The American Weekly*

and iridium per ton to make it one of the richest mines in the world, if only the ore can be reached in quantity.

The writer has for some years been in close touch with this most interesting investigation. It has led him to conclude that what we have here is a collision with the head of a small comet. The nucleus must, however, have consisted of separate masses packed together more closely than usually assumed. As the hole is 4200 feet in diameter it has been conceded that the cross-section of the striking mass must have had a diameter at least one-tenth as large. In addition for some miles on either side, i.e., this distance out into the coma, there were isolated masses which formed the meteorites, picked up on the surface around the crater. As for the shape and mass of the main body, indirect investigations by various scientists who have just attempted to solve the problem lead to widely differing results. By analogy with comets in general, as well as other reasons, the writer has been inclined to accept an approximately spherical shape, with a diameter not less than 400 nor more than 800 feet.

Frankness forces the confession, however,

that so many unknown quantities are present that any solution must depend on assumptions in part, and the truth will only be known when the miners actually penetrate the mass with a tunnel. We do not even *know* but that only one great mass will be found, though we *believe* there is every reason to think it consists of many smaller ones packed together. In any case when the mining is brought to a successful conclusion, we will at last know what the nucleus of a comet looks like, and how it is constituted. This knowledge will be of incalculable value, as it will help prove or disprove many theories presented in various works on astronomy and geology. Its bearing on theories of evolution will be especially important.

THE SIBERIAN METEORIC FALL

On the early morning of June 30, 1908, took place the most remarkable astronomical event of the twentieth century, namely, the fall of an immense object from outer space upon the Earth. It struck in central Siberia,[3] 400 miles north of the Transsiberian railroad, and

[3] *Scientific Am.*, 139, 42–4, 1928.

in a region sparsely inhabited by a few native tribes. Due to these circumstances, and to the fact that there were no scientists near the point of fall, the circumstances were not generally known for many years afterwards, and it was not indeed until 1927 that an expedition under Prof. L. A. Kulik finally penetrated to the spot itself.

It is not possible here to enter into the details of how the story was gradually pieced together, until at last we have a complete account of the event itself, as well as descriptions of the region as it now is. But the known facts will be given—those from scientific sources first. The concussion due to the blow against the Earth's surface was recorded on a seismograph at Irkutsk, 900 km. away and the air-wave at the same city. The latter was also recorded by a barograph at Kirensk, over 400 km. away. Sounds were heard to the south and east of the end point for a distance of more than 1000 km. About the same date a meteorite fell in the Kiev government.

The approximate position of place of fall is longitude 101° east, and latitude 60° north. It lies in a region in which mountains, rivers, swamps and forests abound. The particular

spot is a plateau between two rivers, the Podkamennaja Tungaska and the Chunia, and is quite surrounded by mountains, making a sort of natural amphitheatre.

Although it was nineteen years after the event before the party of Professor Kulik penetrated to this place, thus giving a chance for considerable new growth to take the place of any that had been destroyed, and for erosion to partly obliterate the effects, still what he found was most amazing. In the central area, having a diameter of perhaps 2 miles, there was a sort of shallow depression, the ground showing signs of having been violently pushed sideways, as for instance when a stone is dropped into thick mud, so that ridges still could be seen. Inside this area were 200 "shell-holes" or craters, varying from those only a yard or two in diameter to one 50 yards across. These had steep sides but due to the swampy nature of the ground and the artificial depression they were mostly filled with mud or mire.

In this area proper the trees had been destroyed, but for miles around on every side could be found trees by the tens of thousands lying with their tops away from the center,

where the meteorites had struck the ground. The few trees that here and there remained standing in somewhat protected places were stripped of their bark and branches. Those as well as the trees on the ground were seared, as though touched by the heat from a giant torch. It is stated that the total affected area was from 30 to 40 miles in diameter.

Attempts to dig up a meteorite from the bottom of one of the small craters were unsuccessful, due to the swampy ooze and water that constantly filled the depression. It is quite impossible to make an intelligent estimate as to just how deep these masses lie. But in 1928 a few meteoric fragments were found on the surface. Kulik is said to have estimated the total weight of all the fragments as being about 40,000 tons. Certainly those that made the largest craters must have been yards in diameter or they could not have dug out so large a hole.

Accounts by native Tungus, who were relatively near the spot, and by Russians at a great distance, who yet heard the sounds or felt the effects, agree in the main details. The day was clear, and the terrible noise was likened to thunder or artillery fire. The

appearance itself to an observer at Kansk, 600 km. distant, was described as a circular glow half the size of the Moon, of a bluish tinge, and moving rapidly. The glow left a bluish track, stretching along almost the whole path and afterwards gradually disappearing from the end.

A vivid description was given by a Russian, steering a large boat on the Angara River. His account was as follows: "In the north a bluish light flashed, and from the south a fiery body, much larger than the Sun, flashed, leaving a broad light band. Then such a cannonade arose that all the workers ran into the cabin forgetting the danger from the rapids. The first sounds were weaker but quickly grew." The sound effect, on his supposition, lasted about three to five minutes. The force of the sounds was such that the boatmen were completely demoralized.

One native Tungu had a herd of 1500 deer feeding in the region; of these most were lost, only the carcasses of some being found. Another native, "three days' march" from the place, had his hut knocked down, the top blown away by the wind, his brother stunned and his deer scattered. Another man at

Varovara at a distance of over 30 km. described it thus: ". . . . in a northwest direction appeared a kind of fire which produced such a heat that I could not stand it. . . . . And this overheated miracle I guess had the size of at least a mile. But the fire did not last long, I had only time to lift my eyes and it disappeared. Then it became dark, and then followed an explosion which threw me down from the porch about six feet . . . . but I heard a sound as if all houses would tremble and move away. Many windows were broken, a large strip of ground torn away, and at the warehouse the iron bolt broken."

On this date the Earth was very close to the orbit of Pons-Winnecke's Comet, distant about 0.03 astronomical unit only. This comet in 1916 gave a fine little meteoric shower, and since then we have had many splendid fireballs at this epoch, some of which doubtless follow the same orbit. There is some real reason[4] to suppose that the masses falling in Siberia moved in this same orbit and were a fragment of the original comet, broken off ages before, and itself forming a small comet.

[4] V. A. Maltzev.

Everything apparently can be explained on this supposition, namely, that a small comet entered our atmosphere on the date mentioned and having traveled through it for some hundreds of miles from S.S.W. to N.N.E. on a sloping path, finally struck the ground. The pattern of the craters is exactly what would be expected from a nucleus of such small total mass, whose separate units would be not very close together. The accompanying coma, if indeed such a small nucleus could possibly hold one, was simply lost or mingled in the air that, once the nucleus had penetrated our atmosphere, was forced between the solid units. As these came down they carried in front of them a great mass of air, under terribly great pressure which increased as they came lower, and which was also at high temperature. This immense piston of superheated air was what did the major damage; when it struck it annihilated things in the central area, then escaping sideways it tore down and seared the forest for miles around. The crater or pits were, of course, made by the solid masses themselves, but the damage done by them was small compared to that by the air blast.

It need hardly be added that had this occurred over a city or in a thickly populated area the resulting loss of life and damage to property would have been appalling. It seems there was quite enough energy to level any city and superheated air to kill all of its inhabitants, much as St. Pierre was destroyed in 1902, though from another cause.

Attention having been brought to such craters by these two great examples search made elsewhere has revealed several probable cases. One of them,[5] 530 feet in diameter, 18 feet deep inside, and with a rim only 2 or 3 feet above the plain, has been found in Ector County, Texas. Small pieces of magnetic metal were picked up around this in a preliminary survey.

Another interesting set of craters,[6] which was very probably meteoric or cometary in origin, is found in Esthonia on the island of Oesel. The main pit is 300 feet in diameter, surrounded by a wall or rim which stands 15 to 20 feet high on the outside. Inside is a small lake. Around it lie a dozen other holes

[5] *Proc. Acad. Nat. Sci., Philadelphia,* lxxx, 307, 1928, D. M. Barringer, Jr.

[6] *Scientific Am.,* 139, 45, 1928.

ranging from 15 to 100 feet in diameter. The rocks on the main crater's rim are tilted up, and below the floor deposits of dolomite powder and larger stones are found. These facts, as well as the crater's shape, make a meteoric origin likely, as they parallel what are found at Meteor Crater, Arizona. It is hoped that exploration of some of the smaller craters will be undertaken, as it appears that meteoric fragments should be found relatively near the surface, if this theory of their origin is the correct one.

CHAPTER XV

Origins of Comets

To explain how comets originate is such a difficult problem that many writers of books on general astronomy make no serious attempt even to suggest a theory. Others dismiss the question with as few words as possible, leaving the reader quite bewildered as to what the writer intended to advance as a tenable opinion. Further, it is difficult to find any place for comets in the Nebular Hypothesis of Laplace, which was so generally accepted during the nineteenth century.

First, Carrington may be quoted,[1] who showed that if comets moved according to chance distribution through space, then more would meet the Solar System than could overtake it. Also if they originated outside of our system, orbits with eccentricities much over unity, i.e., strongly hyperbolic, would be the rule rather than the exception. We find that comets' orbits fulfil neither condition.

Miss Agnes Clerke wrote as follows,[2] "We

[1] *Mem. R. A. S.*, 29, 335, 1860.
[2] *History of Astr.*, 370, 1902.

conclude then that the 'cosmical current,' which bears the solar system towards its unknown goal, carries also with it nebulous masses of undefined extent, and at an undefined remoteness, fragments detached from which, continually entering the sphere of the Sun's attraction, flit across our skies under the form of comets. These are, however, almost certainly so far strangers to our system that they had no part in the long processes of development by which its present condition was attained. They are perhaps survivors of an earlier state of things, when the chaos from which the Sun and planets were to emerge had not yet separately begun to be."

The two possibilities, as seen twenty years ago, is thus summed up by Chambers:[3] "Two provisional answers suggest themselves: either (1) comets are chance visitors wandering through space and now and again caught up by the Sun, or by some of the major planets . . . . and compelled to attach themselves to the Sun and by taking elliptic orbits to become permanent members of the solar system; or (2) they are aggregations of primaeval

[3] *The Story of the Comets*, 184, 1910.

matter not formed by the Creator into substantial planets, but left lying around in space to be picked up and gathered into entities as circumstances permit."

In the 1922 edition of Newcomb-Engelmann, page 439, we find it stated that "the most probable opinion as to the origin of comets is that they take their origin in collections of matter, which at great distances accompanies the Sun in its wandering through space."

Leuschner[4] expresses his opinion as to the origin of comets as follows: "The short period comets, according to the well-known 'capture' theories are supposed to have had their orbits changed by Jupiter into very short-period planetary orbits. Such cases can actually be traced. It is natural to suppose that comets in general represent the left-over material from the original nebula which did not condense into the Sun or one of the major planets. Not all this material may have been left over at the outskirts of the solar system beyond the orbit of Neptune. We are justified in assuming that there may be a belt of such left-over

[4] *Pub. A. S. P.*, 39, 294, 1927.

material at least about the largest of the major planets which is Jupiter and that the Jupiter group of comets has come into existence from Jupiter. This of course does not preclude the capture of some of the comets coming from the outskirts by Jupiter and the change of their orbits into short period orbits. Whether originally near Jupiter or at the outskirts of the solar system comets in general may represent the original condition of minor planets."

The ideas above expressed fall in general under the theory known as "The Home of the Comet." This "home" or nebulous shell must partake of the motion of the Sun through space towards the solar apex. Its distance may be estimated at from 10^4 to 10^5 astronomical units. Bosler[5] says: "Strange as this idea may appear, it is only a literal translation of material facts: it is not even a hypothesis, but a convenient manner of depicting objective reality, as it has been revealed by modern research."

However, this theory gives us no inkling as to how such a body as a comet could form under the conditions that must be expected to

[5] *Astrophysique*, 438, 1928.

exist in such a nebulous shell, or why a given mass of it should start towards the Sun, while others did not simultaneously do so.

Crommelin, one of the greatest living authorities on comets, seems somewhat inclined to consider a solar origin possible for comets which have their perihelia near the Sun, especially for the group including the Great Comet of 1882. He bases this upon the knowledge that solar prominences are driven off with immense velocities. He feels that this explanation is not adequate for comets whose perihelion distances are unity or greater.

R. A. Proctor about sixty years ago suggested that the comets were expelled from the planets to whose families they "belonged." At present, recent researches have proved the outer visible surfaces, which are, however, merely the tops of cloud layers surrounding Jupiter and Saturn, are of the order of $-140°$ and $-150°$ Centigrade. But Crommelin,[6] in view of the appearances of spots on the planets, which were evidently deep-seated in origin, thinks it possible that matter may be

[6] *Ency. Brit.*, xiv, 5, 103, 1929.

driven away from these bodies at such speed that it will not return. Something analogous to super-volcanic eruptions is meant. If such matter had velocity enough it would leave the planet and form comets. If this theory is true, an explanation would be given as to how a fresh supply of comets is produced, to take up the wastage which we see constantly going on.

Schiaparelli[7] thought comets formed a sort of stellar current, moving along with the Sun. He said: "The meteorites may be comets of other suns, which, under their heating action have already by frequent and great emissions of jets and tails lost all or nearly all of their containing gases; while our Sun has not yet extracted from all its comets and dispersed in space the total amount of the gas that they originally contained. Finally, comets and meteors may differ among themselves only in the diversity of the places attained in their evolution."

Baldet[8] basing his conclusions on the studies made at the 1927 return of Pons-Winnecke's Comet, as well as on extensive work done by

[7] *Bul. Astr.*, 27, 250, 1910.
[8] *Bul. Soc. Astr. de France*, 41, 401, 1927.

him on others, says: "Even supposing that Pons-Winnecke's Comet came from infinity and was captured by Jupiter, which is not demonstrated, we must admit that it is of relatively recent formation. The same reasoning applies evidently to other comets. . . . . But it is sufficiently remarkable to note, in finishing this study, that modern work upon comets, both in astronomy of position and astrophysics, lead us little by little to see them as of recent formation; it is even possible to think that comets must have their birth in our own time."

Baldet further quotes Crommelin's opinions as to planetary origins with at least tentative approbation.

Chamberlin in his *The Two Solar Families*[9] has advanced another hypothesis which has certainly the recommendation that it is complete in itself, whether it can be adopted or not. In fact it is so fully explained that it is difficult to give a brief yet fair résumé.

The validity of Chamberlin's conclusions depend, almost wholly, upon the correctness of his assumptions about the formation and

[9] Page 251 *et sec.*

actions of his smallest unit, called a chondrulite. He calls attention to particularly vigorous eruptive prominences on the Sun, and to the fact that in some cases the parts received additional impulses after leaving the Sun's surface. This material[10] is first hot and gaseous, "but by reason of its divergent projection, its intrinsic expansion, and its radiation, as it sweeps out into interplanetary space, it is rapidly cooled below the volatile temperatures of the main materials that make up the chondrulites. These are thereby forced to form precipitates, and these in time naturally aggregate as they are forced one against another by the agitation in the projected mass. The minute accretions are the primitive chondrulites. They embraced practically all kinds of matter precipitated." Also they were subject to sharp collisions. This would explain their fragmented structure. "The scattered and mixed state of the fragments is clear evidence that the chondrulites were not formed in place."

In the early stages of the driving out of these hot gases, the conditions were certainly

[10] *Loc. cit.*, p. 262.

dispersive. But when such matter reached zones beyond the last planet, such action was partially screened by intervening matter, while for the same reason the gravitational pull towards the Sun was increased. So the chondrulites in general lost speed the further out they went. Most of them would eventually be turned back, and would then have to revolve about the Sun in elliptic orbits of very high eccentricity. Some of them also had grown constantly by accretions, becoming the true chondrulites. The latter were thus a product of selection; also when any one reached a given size (i.e. mass) it inevitably turned back towards the Sun, gravitation overpowering the forces of outward propulsion.

Also in this outer zone where their velocity was almost zero, their mutual attractions became more of a factor. So when such a mass of chondrulites were moving in nearly parallel paths, Chamberlin believed that in this outer zone their mutual attractions would tend to make them gather into swarms or groups. Such swarms became the heads of comets; those chondrulites which did not so gather became the ordinary sporadic shooting stars or meteors. Further the idea is ex-

pressed that comets, on subsequent visits to this outer zone after a perihelion passage, partly replenish their stores of fine dust and gas, which are considered as being present in some quantity in this zone.

The detailed behavior of comets is dealt with at length by Chamberlin, after he has explained the above hypothesis of origin. But as pointed out the whole stands or falls on the assumption that chondrulites are formed in the manner outlined.

Recent observations by Evershed[11] bear most favorably upon the above theory. "It is curious to observe on these photographs the intricate structure assumed by a mass of gas projected into space and freed from the restraining forces in the photosphere. It does not diffuse away uniformly, but appears as a mass of fine filaments and interlacing streams of gas, seemingly knotted together at one point, which suggests that light pressure alone is not an adequate explanation of these eruptions." Reference is here made by Evershed to a rare type of prominence seen on November 19, 1928. This at 7^h 50^m I.S.T.

[11] *Observatory*, 52, 38, 1929.

was 3′ to 4′ high, at $9^h\ 3^m$ was 21′ high; still remaining bright when clouds came over.

In a recent paper by N. T. Bobrovnikoff[12] the question of disintegration of comets is studied, and his investigations bring him to interesting conclusions about their origins. First he proves, basing his results on 94 periodic comets, that there is a definite correlation between the absolute magnitude of a comet and the value of the dispersive function $\phi\ (a, e)$ derived theoretically. And also that the abundance of gases in the head and the tail of comets shows correlation with the same function $\phi\ (a, e)$. In other words that both show certain dependencies on the major axes and eccentricities of the orbits.

These conclusions are partly based on work by Holetschek who proved that the maximum length of comets' tails depended upon their absolute brightness, and by Vsechsviatsky who showed that the average absolute brightness of comets increased with the increase of the inclinations of their orbits.

Bobrovnikoff says: "In their obedience to the law of disintegration comets form a

[12] *Lick Obs. Bul.*, No. 408, 1929.

system all members of which follow the same career with the same ultimate fate. The matter in comets must be in a very peculiar state of excitation which does not occur often in the universe. Yet all comets have fundamentally the same spectrum. These facts constitute strong evidence for the common origin of comets.

"The system of comets is closed, that is, we have no influx of fresh comets coming from the depths of the universe. If we had any, it would affect the correlation between their orbital elements and the average absolute brightness. Indeed such correlation would be incomprehensible.

"On the other hand, this correlation shows that the disintegration of comets is an irreversible process. There is no building up of new comets from the meteoric and gaseous matter diffused in space. . . . ."

He then develops the argument that comets can scarcely be more than 1,000,000 years old, for if older they must before this have wholly disintegrated. He also shows that comets are evidently true members of our Solar System, yet that their ages are not comparable to that of the planets. Other investi-

gators have shown that the distribution of the perihelia of comets' orbits show regularities which can scarcely be explained, in his opinion, if these bodies have been in the Solar System from its origin. His solution is that all comets were captured, at about the same time, and not longer than a million years ago. The Sun appropriated them during one of its passages through diffuse clouds of obscuring matter.

In comment on this theory it may be said that in common with nearly all others, while it gives a possible place and time from which comets came, it offers no explanation as to why bodies of such peculiar structure were to be found there, or as to how matter in such a diffuse cloud could form into comets. The theories which have been outlined are those which have been advanced during the last half century and which, in the writer's opinion, deserve consideration.

CHAPTER XVI

Conclusions

"Wandering stars, to whom is reserved the blackness of darkness forever."

In such a difficult problem as that of explaining the origin of comets, and one which many eminent men have attempted with indifferent success, it would be presumptuous to believe that an entirely satisfactory solution can be given in the present state of astronomical knowledge. In the previous chapter many opinions have been quoted, and certain difficulties pointed out. Here the writer will discuss the subject from his own viewpoint, hastening to add that he does not claim to have reached a satisfactory solution, but can only hope to indicate what may prove to be useful lines of approach.

First, the origin of comets can scarcely be discussed without some previous knowledge about that of the evolution of the Solar System in general, that is, unless we accept Bobrovnikoff's theory that comets have recently been acquired by the Sun, and are not really members of his family, but only adopted

children. Or we might adopt the theory that they are still being created by planetary eruptions. This former theory has attractive features, the best being that it disposes of the difficulty of explaining how comets could have lasted as long as the planets have, i.e., were created at the same time as these latter. Admitting this excellent feature, still it does not appear wise to deny a solar origin to comets until all possible (and reasonable) explanations have been exhausted. As the writer does not believe that this has yet been done, certain ideas will be outlined which may offer a possible explanation of the time difficulty in an assumed solar origin. It is further useful to do this, for in Bobrovnikoff's theory, which assumes capture of the comets as the Sun passed through a nebulous region, no mechanism is suggested as to how such a body could be formed under the conditions that are supposed to exist in a nebula. luminous gases

In all that follows a catastrophic origin of the planetary system, due to the near passage of another star to our Sun, is postulated. It seems quite certain that the difficulties raised against the Nebular Hypothesis of Laplace are insuperable, so this need not be discussed

here. The Planetesimal Hypothesis[1] of Chamberlin and Moulton is, in its broad outlines, assumed as explaining correctly the genesis of the planets of the system. The various modifications of this hypothesis, due to certain English astronomers,[2] while differing in details, are still in the writer's opinion based wholly upon the one mentioned as to fundamentals, and would not have been advanced had not the other first appeared.

The latest exposition of the Planetesimal Hypothesis[3] was written by Chamberlin, just before his death. Here he gave his personal ideas as to the formation of comets and meteors, which formed the second of the solar families discussed. The writer, while accepting in general the first part of the book, namely, that giving the original theory of the formation of the planets, has to disagree with the second half. But he believes that the ideas expressed in the first half may be used in a more correct explanation of the origin of comets and meteors.

[1] F. R. Moulton, *Introduction to Astronomy*, Chap. xv, 1906.

[2] Sir James Jeans, *Problems of Cosmogomy and Stellar Dynamics*, 1919.

[3] Chamberlin, *The Two Solar Families*, 1928.

The planets are assumed to have come from the zones near to and parallel with the Sun's equator. Here the tidal forces were great and were aided by the explosive forces lying in the spot zones. It seems, however, that in addition polar eruptions would be caused, though of smaller amount, for the following reason.

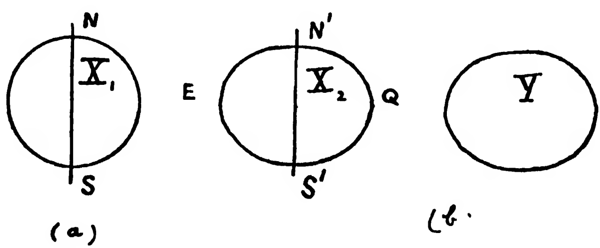


FIG. 4

In figure 4, (*a*) represents the undisturbed spherical Sun, (*b*) the Sun with the immense tides, which are due to and pointing towards and from the disturbing star *Y*. X_2 is of course exaggerated as to probable heights of the tides. Now the material that heaped up at *Q* and *E* had to come from *somewhere*, and left a "low-tide" belt at right angles, that is extending completely around the Sun, half way between *Q* and *E*, and passing through

each pole. This meant that, surface material being removed, hotter and presumably more active or explosive material was brought to or near the surface. Would not great eruptions of this lower-lying material then take place all around this belt, including the part of it passing through the polar regions, which are usually relatively quiescent? Consider a mass M thrown out from N' and one R from S'. If projected vertically, the attractions of the other star would draw them over toward it, in other words give curvature to their paths. But the directions of their motion would be *exactly opposite.* Here we have an easy explanation of masses in our system which from birth had retrograde motions, as, off-hand, we may say that at least half of these masses went one way, half the other. If this explanation can be accepted, we get all possible inclinations for such bodies. Also, if their material was in general lower-lying than that which was torn off at Q and E to form the planets, bodies, differing somewhat from the latter in their constitutions, might be expected. Another point is that material torn from the other sun would mingle with that torn from our own, and so would be available in form-

ing bodies in our system. Both motions and physical conditions might be largely modified thereby.

The idea here advanced is that comets had such an origin, also many asteroids and perhaps some bodies that are now satellites of certain planets. The argument in favor of the inclusion of these two latter classes will now be developed.

That there can be no hard and fast line of demarcation between asteroids and comets is proved, for instance, by asteroids Nos. 944 and 1927 BD.[4] Their orbits are quite cometary. If these bodies showed either a coma or a tail they would be classed as comets. Both objects are, however, sharply stellar in appearance. Other asteroids have orbits of high inclination and large eccentricity, not unlike short period comets. It will be objected that we have no asteroids with retrograde motion, while half of the comets have it. But let us point out that all very short period comets have direct motion and small inclinations. There are a few comets of medium period and retrograde motion. Cannot this

[4] *Meteors*, 264 *et seq.* Also *Jour. of Franklin Inst.*, 207, 733 1929.

be interpreted to mean that comets (or asteroids) of short period, retrograde motion, and small inclinations had a poor chance for survival? They were, to express it crudely, swimming against the stream, when, according to hypothesis, the whole region within the orbit of Jupiter must have been filled with planetary building material. Therefore, in time, collision with direct moving material could scarcely be avoided. The possibility is then suggested that asteroids and comets had the same kind of origin. In the first case it seems probable that enough material came together under favorable circumstances for its mutual gravitation to draw it all into a compact or comparatively compact body. In the second case, the circumstances were unfavorable and the material less.

With regard to both asteroids and satellites, it seems to have been generally tacitly assumed that they were solid, continuous bodies. But on what is this based? So far as asteroids are concerned we have no way to determine the masses of any of them, nor are we liable to do so unless in the cases of the very largest a comet should pass extremely near one of them. With satellites we are in a more

favorable position, and very curious results follow in some cases. For instance the fourth satellite of Jupiter—Callisto—turns out to have a density of only 0.58. Also for the satellites of Saturn we find Mimas, 0.24; Enceladus, 0.52; and Tethys, 0.54. These values are calculated from data in Table IV of *Astronomy* by Russell, Dugan and Stewart. How can such low densities be explained on the basis of a single, continuous, solid body? For it seems impossible to assume these small bodies are still in the gaseous or liquid form. Is it possible that such satellites furnish us with examples of bodies that are in constitution half way between a typical solid satellite or asteroid, and the nucleus of a typical comet? Is it possible that the variability of some asteroids and satellites could be explained on the basis of their being a rather compact group of separate masses rather than one continuous body? Remember that practically all asteroids we can see are within the orbit of Jupiter; we do not know about those outside. Again we find meteorites and fireballs with orbits of all inclinations. Does it not seem probable, therefore, that the action of Jupiter, plus collisions with other masses,

did not permit retrograde asteroids of considerable size to survive? Very small ones with orbits of high inclination would escape discovery except under most favorable circumstances. But these actions just mentioned might well permit the survival of retrograde comets of long period, which would spend so little of their life within the critical region.

Calling up again the Meteor Crater and Siberian cases, here we have one body, which if it could have been seen at all would have looked like a tiny asteroid, the other like a tiny comet. Yet each are technically comets. Again recent work at the Lick Observatory shows that spectrograms of asteroids are remarkably weak in the ultra-violet region and this, in the opinion of the observers, connects these bodies physically with the nuclei of comets. Also the presence of small retrograde satellites in the system of Jupiter and Saturn, outside the orbits of the direct moving satellites of these planets, proves that retrograde bodies of small size survive only under special conditions. So while the chain of evidence is far from complete, these various facts are certainly very significant. The probable reason we see so few cases of

"stripped nuclei" of comets—to borrow a physical term—such as the Meteor Crater nucleus possibly was, is that such a comet, stripped of its coma, assuming indeed it ever had one, would usually be too small to be seen at any distance from the Earth. We can by no means assume that many do not pass us annually undetected.

Next as to the time element, which is a most serious difficulty. Let us assume the time interval since the formation of our system to be 8,000,000,000 years, a figure now in good repute. Then a comet with a period of 1000 years would have returned 8,000,000 times, and so on for any period we may choose.

With this in view, we must, acknowledging the facts of cometary disintegration, admit at once that all comets which *originally* had short periods have long since disappeared as comets. They *may* survive as asteroids, in given cases. The same fate doubtless befell those with original small perihelion distances. To explain the present state of things we are then forced to postulate that all comets of short or even moderate periods have been recently turned into smaller orbits, through planetary influences, or by passing through

other resisting media found further out in space. This is simply an extension of the capture theory on a much grander scale.

In explanation, the idea is that it would not make any difference how often a comet came to perihelion, so far as its being disrupted or losing its gases are concerned, provided only its perihelion distance was great. We are not held to any particular figure for the probable critical distance, but it may be that a nearest approach of 10 astronomical units would still leave a comet unaffected. If this limit is considered too low, fault could hardly be found with 20 or 30 units, as the limiting distance. This would still leave the comets subject to planetary perturbations, which in the course of ages would switch a certain number into smaller orbits.

It may be added that we have no data whatever on comets with perihelia as much as 5 units from the Sun, so disproof of this hypothesis is at present difficult. That it postulates the evolution of an immense number of comets, when our system came into being, is obvious. That further it requires the "capture" of a certain number almost yearly in the sense that their orbits are being made gradu-

ally smaller so that in time they come into our range of vision, is also true. Mathematical investigations of such a problem in isolated instances have been worked out by many, so the process is more or less understood.

With full realization that nothing at present further than probability can be adduced in favor of this theory, it is still advanced in the hope that it may stimulate others toward attempting its proof or disproof.

From our studies it is believed that we have a fair idea of what composes a comet, and how the matter is arranged. Then the last question comes up, how in detail did such a curious and complex body evolve? Would the same forces that formed the planets suffice for comets? Here the writer admits that he has not even an intelligent guess to offer in addition to what has already been said, and this he believes is wholly inadequate. He only ventures to say, as a mere matter of opinion, that in the chaotic and diversified conditions following the birth of our planetary system, it would appear that there would have been more chances for the evolution of such bodies than in a nebula.

In conclusion, comets still offer some of the most surprising phenomena and perplexing problems in the whole realm of astronomy. It is not improbable, indeed, that the mystery of their origin and formation will be the last problem, dealing with the evolution of the Solar System, which astronomers of the future will be called on to solve.

APPENDIX

For the benefit of those readers who are not familiar with the elementary facts about orbits and yet desire a little information on the subject, the following pages have been added.

First it should be said that comets, as we have seen, move in three possible types of orbits about the Sun: the ellipse, the parabola, and the hyperbola. In all cases the Sun occupies a focus. The Earth itself revolves around the Sun once per year in an ellipse that differs but little from a true circle, in other words has a small eccentricity actually equal to 0.0167. The semi-major axis of our orbit, technically called the mean distance to the Sun, is known as the astronomical unit, since it is the unit used for all larger distances within the Solar System. It equals 92,870,000 miles or 149,450,000 kilometers. The plane of the Earth's orbit is known as the plane of the ecliptic. This is used as the plane in the Solar System to which we refer other orbit planes. The circle in which this plane cuts the celestial sphere is the ecliptic itself, the path followed by the Sun in its apparent annual circuit of the heavens as well as that followed by the Earth as seen from the Sun.

In order to define the size, shape and position in space of the orbits of other bodies, as well as their positions in their orbits, so-called elements are derived. For a body moving in an ellipse, seven are necessary; for one in a parabola, only five. This at

once indicates why the latter type of orbit is easier to compute. In the ellipse, two (a, e) define its size and shape; three (i, Ω, ω) define its position in space; two (Pe, T) define the position of the body in its orbit at a given date. Using figure 5, we define these quantities as follows:

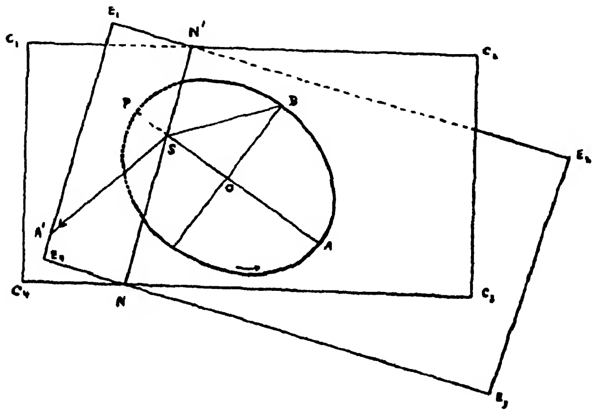


FIG. 5

(1) $a = OA = OP$ The semi-major axis of the ellipse, defining its length.

(2) $e = \dfrac{OS}{OP} = \sin\phi = \dfrac{OS}{BS}$ The eccentricity of the ellipse, obviously a ratio defining its semi-minor axis $OB = b = a\sqrt{1 - e^2}$.

(3) $i = \angle C_4NE_4$ The inclination of the plane of the orbit to the plane of the ecliptic. If $i < 90°$ the motion of the comet is direct. If $i > 90°$ the motion is retrograde.

(4) $\Omega = \angle A'SN$ The longitude of the ascending node, which is the angle measured in the plane of the ecliptic between the lines SA' and SN. Where the line SN cuts the orbit is the point in which the object comes from below the plane of the ecliptic as it moves towards A', i.e., the First of Aries.

(5) $\omega = \angle NSP$ The angle, measured in the direction of the comet's motion, between the lines SN and SP.

(6) Pe The period, i.e., the time interval in years and fractions that it takes the body to make a complete revolution around the Sun.

(7) T The epoch, the date at which it passes P.

We should further define P as the perihelion point, i.e., that point on the orbit nearest to the Sun. $SP = q = a\,(1 - e)$. Also A, the aphelion point, is the most distant point on the orbit from the Sun: $SA = a(1 + e)$. In place of (5) many books give the longitude of perihelion $\pi = \Omega + \omega$. Obviously if Ω and ω are known, π is also known. It should, however, be carefully noted that $\Omega + \omega$ is the sum of two angles lying in different planes. Also in place of (6) we frequently have given the mean daily motion $\mu = 1296000''$ divided by the period expressed in days. Again it is obvious that if either μ or Pe is given the other can at once be derived.

In the parabola, by definition $e = 1$, the curve is an open one, and the semi-major axis is infinite. Therefore there can be no period. The elements i, Ω, ω, and T are defined as in the ellipse. We have, however, the

additional element q = the perihelion distance, or the distance SP. It is needless for our purposes here to describe the hyperbola further than to say that it too is an open curve so that a body moving around the Sun in such an orbit would never return.

As noted in earlier chapters most comets are said to move in parabolas, clearly keeping in mind what the

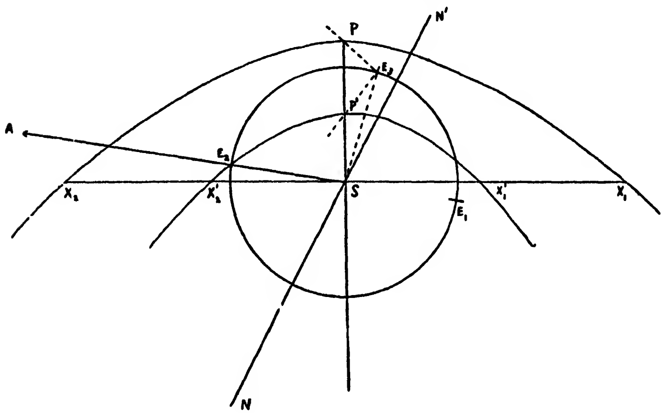


FIG. 6

statement really means. Even most of those known to move in ellipses have orbits of high eccentricity. This being true, we will not make any great error if we assume that any given comet moves, when near the Sun, in a parabola, so long as we are dealing with a rough graphical representation of its motion. In figure 6 we desire to illustrate how the relative positions of a comet and the Earth, when the former is in the visible part of its orbit, may be approximately deter-

mined. The figure is of more obvious value when the inclination is small. The general method is due to Comstock.[1]

Let $E_1E_2E_3$ represent the Earth's orbit, and, as a first approximation, let the plane of the comet's orbit lie in the plane of the ecliptic, i.e., $i = 0°$. Let the line of nodes be $N'SN$. By known properties of the parabola the chord through S perpendicular to $SP = q$ is 4 q in length $\therefore$ $SX_1 = SX_2 = 2q$. Again from celestial mechanics we have for motion in a parabola

$$(1) \qquad \tan\frac{V}{2} + \frac{1}{3}\tan^3\frac{V}{2} = k\,\frac{(t - T)}{\sqrt{2}\,q^{3/2}}$$

in which V is the angle at S between the radius vector to the comet and SP, t is the date, and T the date of perihelion passage, i.e., the epoch. Also k is the Gaussian constant of gravitation, which in terms of astronomical units per day $= 0.0172$.

In the figure $V = 90°$, $\therefore \frac{V}{2} = 45°$, and $\tan 45° = 1$, $\therefore \tan\frac{V}{2} + \frac{1}{3}\tan^3\frac{V}{2} = 4/3$. Also if $q = 1$, we can write the above equation $4\,\frac{\sqrt{2}}{3} = k\,(t - T)$, and substituting the value for k, we find $t - T$ days. This gives the time it takes the comet to travel from X_1 to P, or P to X_2. The equation can be solved most simply for any other value of q by the use of logarithms.

[1] *Pop. Astr.*, 6, 465, 1898.

If SA represents the direction to the First of Aries, and the Earth's orbit be taken as circular, then its radius equals 1. Also the Earth will occupy E_2 at the fall equinox and E_1 at the spring equinox. As it moves $360/365\frac{1}{4}$ of a degree per day, it is easy to find its position on the orbit at any subsequent date, measuring from one or the other of these—the nearest of course. The comet must be at P on the date of perihelion passage. We also saw above how to calculate when it would reach X_2 or was at X_1. Its position at any intermediate date can be accurately calculated from equation (1) if Barker's tables are at hand. These tables are found in Watson's *Theoretical Astronomy*, as well as in other publications. An approximation close enough for rough purposes can be made by interpolating along PX_2, allowing for the fact that the velocity of the comet is considerably greater at P than at X_2.

Having thus found positions for Earth and comet on the same dates, a line joining any two such positions will give both the distance of the comet from the Earth and the elongation of the comet from the Sun. This will permit, by inspection, our finding if the comet is a morning or evening object, and also its position on the ecliptic. Obviously, however, the orbit plane of the comet usually will make an angle with that of the ecliptic. In this case consider the orbit rotated around NSN' as an axis until the proper inclination has been reached. If the angle is large, considerable calculation may now be necessary, but the solutions of plane triangles will suffice for the approximations desired.

As a typical case let us take the elements of Comet 1927*f* (Gale):

T	1927 June 14
ω	209°
Ω	69°
i	13°
q	1.26

Figure 6 has been drawn to scale for these elements, assuming $i = 0°$. The corresponding parabola is $X_1\, P\, X_2$. The second parabola, $X'_1\, P'\, X'_2$, represents an orbit with the same elements except that $q = 0.6$. As the epoch is June 14, this is evidently 8 days before the summer solstice. Hence the Earth will have moved 82° from E_1 and be at E_3, when comet C is at P, and comet C' at P'. We at once calculate that it will take C 155 days to reach X_2, but C' only 51 days to reach X'_1. As the inclination is 13°, both Earth and comet are moving with direct or counter-clockwise motion. Hence the respective angles between the comets and the Sun are PE_3S and $P'E_3S$. Obviously P will rise several hours before midnight and will remain visible until dawn. P', on the contrary, will rise only about an hour before the Sun, and hence be visible in the morning twilight. As i is only 13°, the error of assuming Earth and comets in the same plane will not be a serious one in this case. Other relative positions of the three bodies can be readily plotted and the resulting angles read off and interpreted as above. Also the distance of the comet from either Sun or Earth can be measured off by a scale to quite a fair degree of approximation.

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